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LIFE TEST OF ATTITUDE CONTROL AND STATION KEEPING SUBSYSTEM

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TECHNICAL REPORT AFAPL-TR-69-116

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AIR FORCE AERO PROPULSION LABORATORY
AIR FORCE SYSTEMS COMMAND
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LIFE TEST OF
ATTITUDE CONTROL AND STATION KEEPING SUBSYSTEM

W. F. Krieve

FOREWORD

This report was prepared by the Science and Technology Division of TRW Systems Group, TRW, Inc. The work was performed under the Air Force Aero Propulsion Laboratory, Project 3141, Task 314101, during the period 7 August 1967 to 28 July 1969. The report is submitted in accordance with the provisions of Air Force Contract AF33(615)-3729, "Resistance Jet Attitude Control and Stationkeeping System Development." Messrs. A. T. Molisse and J. W. Geis served as Air Force Project Engineers. The principal contributor to this report was Mr. W. F. Krieve. This report was submitted February 1969.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

R. G. Leiby

R. G. Leiby, Major, USAF
Chief, Propulsion and Power Branch

ABSTRACT

This report describes a life test of an attitude control and station keeping subsystem which uses an electrically-heated ammonia propulsion system. A high-performance ammonia thruster and a zero-gravity ammonia feed system were operated in response to the stimulus of control electronics typical of future military spacecraft. This test was a continuation of a successful one-month demonstration test performed as the final task of a system development program. In total, the test was continued for a period of 752 days, during 540 days of which the system was operated closed-loop. The feed system was operational for the entire test period. It successfully regulated delivery pressure to within a 3 percent deadband under a wide variety of environmental and duty cycle conditions. Three different four-nozzle thrusters were tested, two of which failed due to ammonia corrosion after periods of 5 and 3-1/2 months. The test of the third thruster was terminated after a 6-month period of successful operation. No ammonia corrosion was evident. The thruster characteristics included a delivered specific impulse of 240 seconds at 1500°F. A power level of 14 watts was required to maintain this temperature with no flow.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

1. INTRODUCTION

This report describes the work performed by TRW Systems on the life test of an Attitude Control and Station Keeping Subsystem (ACSKS) which uses an electrically-heated ammonia propulsion system. The effort, which occurred during the period 7 August 1967 to 28 July 1969, was supported and directed by the Air Force Aero Propulsion Laboratory (AFAPL) under Contract AF33(615)-3729.

The ACSKS comprises: (1) an attitude control and station keeping electronics unit, (2) resistively heated ammonia thrusters, and (3) a zero gravity ammonia feed system. The objectives of the program were to determine experimentally the long-term operating characteristics and reliability of a high-performance subsystem which integrates these elements in a manner typical of future spacecraft applications and to implement design changes to achieve the desired performance characteristics.

Following the successful completion of the design, development and demonstration testing of a high-performance attitude control and station keeping subsystem (Reference 1) the subsystem was subjected to a long-term life test. The total life test period, including the demonstration test, extended through a time period of 752 days. Of this time period, the ACSKS components were operated in closed loop for 540 days. During the course of the life test, several problems were encountered with the compatibility of thruster materials. Solutions to these problems were found as a result of data obtained from post-operative analyses of thrusters and from a materials compatibility test program initiated concurrently with the life test program.

The attitude control electronics unit and zero-gravity feed system were operated successfully during the entire life test. The thruster, after modifications as indicated by independent tests, was operated successfully during the final 180-day period of the life test. The attitude control electronics demonstrated the capability of maintaining a pointing accuracy of ±0.1 degree. The thruster demonstrated the capability of delivering a specific impulse of 240 seconds when operated at 1500°F. The power required to maintain this temperature was 14 watts. The thrust level was varied within the range of 0.020 to 0.030 pound. There was a

2-watt degradation in thruster thermal performance resulting from insulation contamination in the test chamber. The zero-gravity ammonia feed system demonstrated the capability of maintaining a pressure control limit of ±1.5 percent around the nominal delivery pressure. These control limits were independent of flow demands required by the various operating modes determined for the mission. The nominal delivery pressures required by the different thrusters to maintain a thrust level of 0.020 pound were in the range of 30 to 35 psia.

2. SUMMARY OF THE PREVIOUS PROGRAM

The life test phase of the ACSKS program was initiated to determine the long-term operating characteristics of an attitude control and station keeping subsystem which uses an electrically-heated ammonia propulsion system. This phase was a continuation of a program that initially included the design, development, and demonstration test of an attitude control and station keeping subsystem. In the first phase of the program, which is reported in Reference 1, a mission analysis was performed to define a general class of spacecraft missions of interest, determine their attitude control and station keeping requirements, and establish a method by which an ammonia electrothermal propulsion system could meet these requirements. Mission parameters defined by the program statement of work were:

• Total spacecraft weight:	2000 pounds
• Altitude:	Earth synchronous
• Thrust range:	0.005 to 0.050 pound
• ACSKS maximum weight:	100 pounds
• ACSKS maximum power consumption:	100 watts
• Total impulse (Hot):	10,000 lb-sec
• Minimum life:	1 year
• Solar array area:	100 ft^2
• Stabilization mode:	Three-axis

In addition to the mission analysis, a control technique survey was performed to determine the best type of electronic control logic to perform the mission requirement. As a result of this survey, the pulse ratio modulation (PRM) approach was selected as the most suitable control logic for commanding the reaction jet pulses.

A complete three-axis attitude control and station keeping subsystem was designed to meet the selected mission requirements. The subsystem has the capability of maintaining an earth pointing accuracy of $\pm 0.1^{\circ}$, provides in-plane/longitude and out-of-plane/latitude station keeping of 23.9 lb-sec per day, and provides the required impulse to remove initial displacements and rates to achieve acquisition.

The thrusters selected for the subsystem were resistively heated, thermal-storage devices. Four thrusters were required for the subsystem and each thruster contained four nozzles located in a plane as mutually orthogonal, in-line, opposed pairs. Each nozzle was designed to develop 0.020 pound of thrust at either ambient temperature or any temperature between 1500° and 1750°F. The ambient temperature represents the condition of no power to the thruster, while the temperature range of 1500° to 1750°F is the condition when the heater element is energized directly from the spacecraft bus voltage. The thrusters use vapor-phase ammonia as the prepellant. They have the capability of increasing the propellant temperature when operated in the heated mode and also decomposing the ammonia into molecular hydrogen and nitrogen. The thrusters are operated in the cold gas mode during initial acquisition when the duty cycle may be high. During normal mode control, the thruster duty cycle will be low; thus, they can be operated hot and deliver peak specific impulse. The maximum hot duty cycle, 2 percent, is required for station keeping.

The ammonia feed system was designed to supply vapor phase ammonia to the thrusters. It was comprised to two storage tanks, each with an independent flow and pressure regulation system. the maximum flow demand that the feed system was required to supply was 4×10^{-4} lb/sec. This maximum demand was to occur during acquisition for a period of approximately 300 seconds. The minimum ammonia storage tank pressure during this 300-second flow period was assumed to 86 psia. The nominal delivery pressure to the thrusters was designed to be 30 psia with a nominal deadband of ±1.0 psi. Tank pressure variations during the entire mission were expected to be between 60 psia and 214 psia.

During the design and development phase of the program, a complete three-axis control system was simulated by an analog computer. Command torques from the thrusters and inertia properties of the spacecraft were also simulated. The acquisition, attitude control, and station keeping behavior of the ACSKS was examined within a range of different initial displacement and rate inputs, disturbance torques, and station keeping rates. The results of these tests are reported in Reference 1.

A series of thruster design analyses was performed to determine (a) insulation configurations that would result in minimum thermal losses, and (b) a flow passage design that would result in nearly complete decomposition of the ammonia when the thruster was operated in the heated mode. Prototype thrusters were fabricated and design verification tests were performed. In addition to these tests, heater element tests were initiated to determine the operating characteristics and life expectancy of various heater element materials and element configurations. Materials compatibility tests were also performed to determine if there would be any detrimental interactions between the thruster structural materials.

The feed system concept selected for the program used capillary flow tubes to regulate the ammonia flow and insure that it was delivered to the thrusters in the vapor phase. In the zero-gravity environment of space in which the feed system is to operate, the location of the interface between the vapor phase ammonia and the liquid phase in the prepellant storage tank is not necessarily predictable. Because of this, as propellant is required from the storage tank, it can exit as either vapor or liquid. The capillary tubes, which are small-diameter tubes with large length-to-diameter ratios, serve as vaporizers for the ammonia if liquid phase is leaving the tank. The capillary tubes are dimensionally sized so that if liquid ammonia enters the tubes, it will be completely vaporized before it leaves. Propellant flow from the tank was controlled by an ON-OFF solenoid valve. The position of the valve was controlled by a transducer through a level detector switch and valve driver assembly. During the design and development phase of the program, flow and heat transfer analyses were performed to determine the capillary tube performance. A heat transfer analysis of the heat extraction process between the stored propellant and the capillary tube was also performed. A prototype feed system was assembled and both design verification tests and pressure regulation interaction tests were performed.

After the design and development tasks of the program were completed, a demonstration test was designed. The purpose of the demonstration test was to determine the operating characteristics of flight-type operational units of an attitude control system. The units used in the test were:

1) A single-axis electronic controller
2) A four-nozzle ammonia thruster
3) A zero-gravity ammonia feed system.

These units were operated in a closed loop mode. In this mode, the control electronics receive an input rate and position error signal. This signal is converted into an appropriate thruster propellant valve command. An ON valve command will result in propellant flow through the thruster, causing an impulse bit. The result of this impulse bit is conditioned by a rigid body simulator to drive a sensor element. An OGO sun sensor-stimulus is used to generate the error signal. Ammonia propellant is supplied to the thruster from the feed system at the desired pressure. The three attitude control units were operated in a vacuum chamber to simulate the pressure environment of space.

3. LIFE TEST

The units used in the life test were flight-type models. They were designed and fabricated to meet specifications typical of those that would be required on a spacecraft. The chamber in which the test was performed was maintained at pressures that simulated the vacuum of space.

3.1 CONTROL ELECTRONICS

The control electronics used in the test was essentially a single-axis unit of the three-axis attitude control system. The single-axis controller consists of the lead-lag network, the pulse ratio modulator, and the valve driver circuits. The lead-lag network is an integral part of the electronic controller. It is an integrating circuit that converts the rate of change of sensor displacement signal into an error signal that is additive to the error signal resulting from displacement. This allows the pulse ratio modulator to both detect and anticipate spacecraft displacement. A schematic of the single-axis controller, which includes the lead-lag network and the pulse ratio modulator, is shown in Figure 1. A schematic of the valve driver circuit is shown in Figure 2. Both the single-axis controller and valve driver are described in detail in Reference 1. The unit, fabricated for the demonstration test, was used throughout the entire life-test phase of the program. A portion of the circuit was bypassed during the later stages of the life test when a pulsing circuit was used to produce the error signals instead of a sun sensor-stimulus unit. A photograph of the actual control unit and valve drivers is shown in Figure 3.

3.2 THRUSTER

The ACSKS thruster is a resistively heated, four nozzle unit. Each nozzle delivers 0.020 pound of thrust. The thruster is designed to heat ammonia to a minimum temperature of 1500°F and decompose it into molecular hydrogen and nitrogen. The thruster is of the thermal storage type and can sustain a propellant pulse duty cycle of 2 percent while maintaining a propellant temperature of 1500°F. The maximum pulse duration is 3 seconds. In order to meet flow requirements of the 2 percent duty cycle, 3-second pulses, and a minimum propellant temperature of 1500°F, the minimum equilibrium no-flow thruster temperature had to

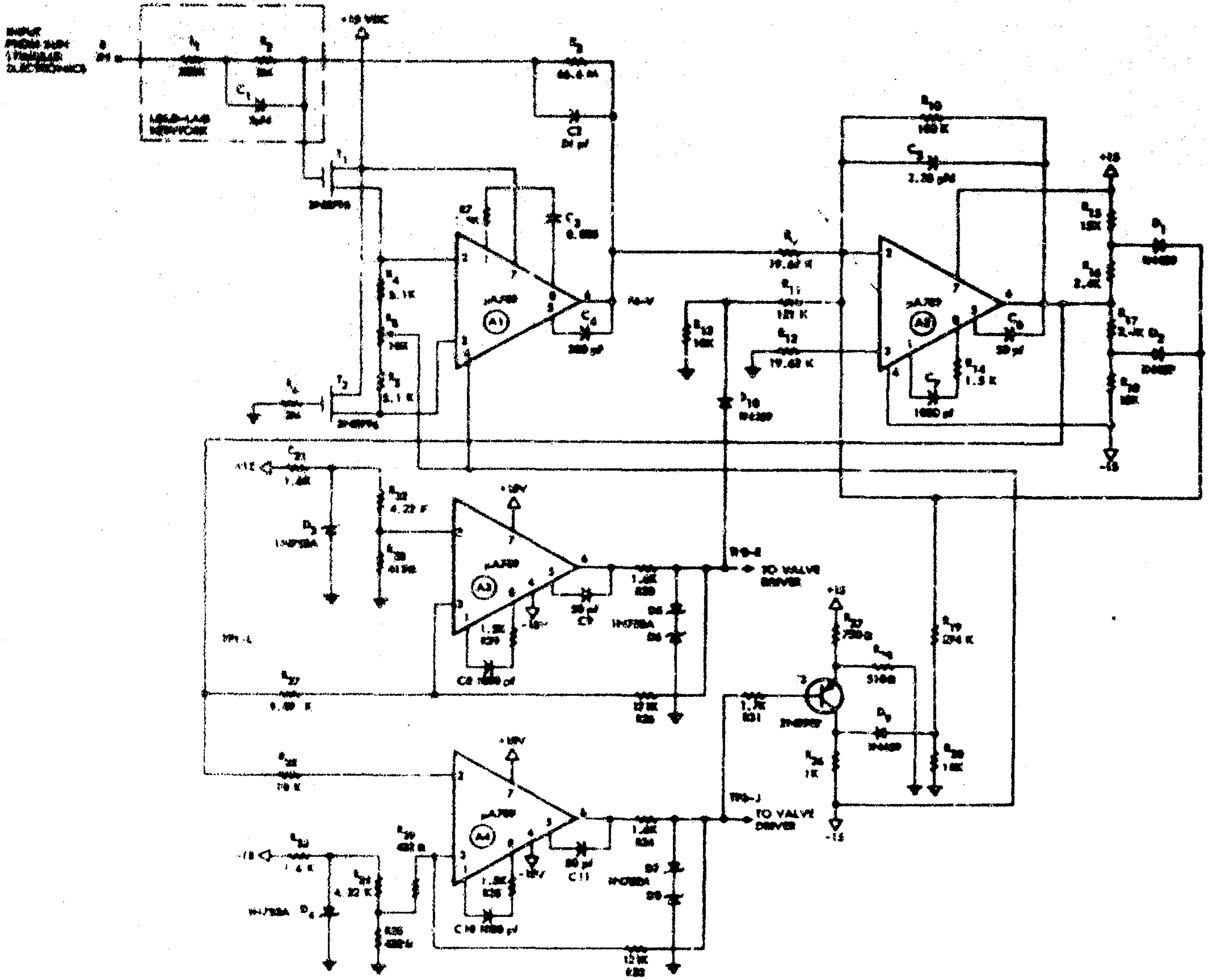
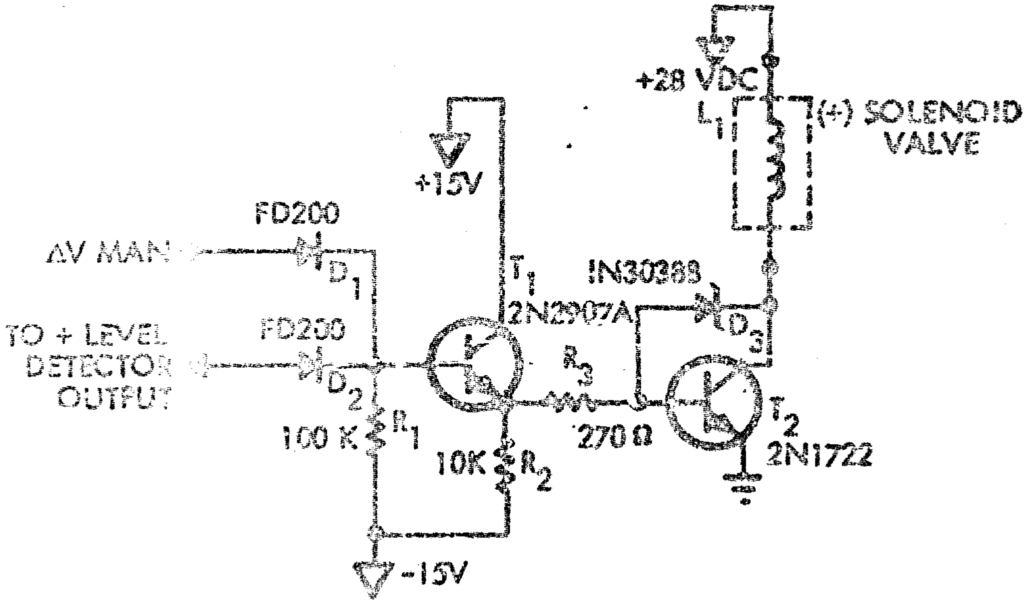


Figure 1. Single Axis Cont oller Schematic



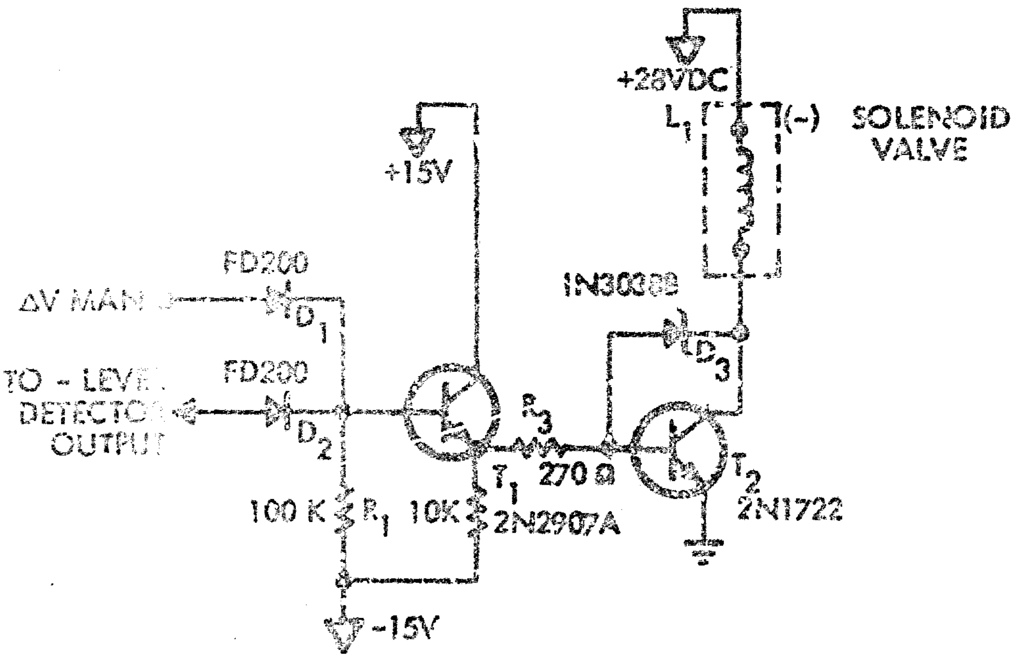
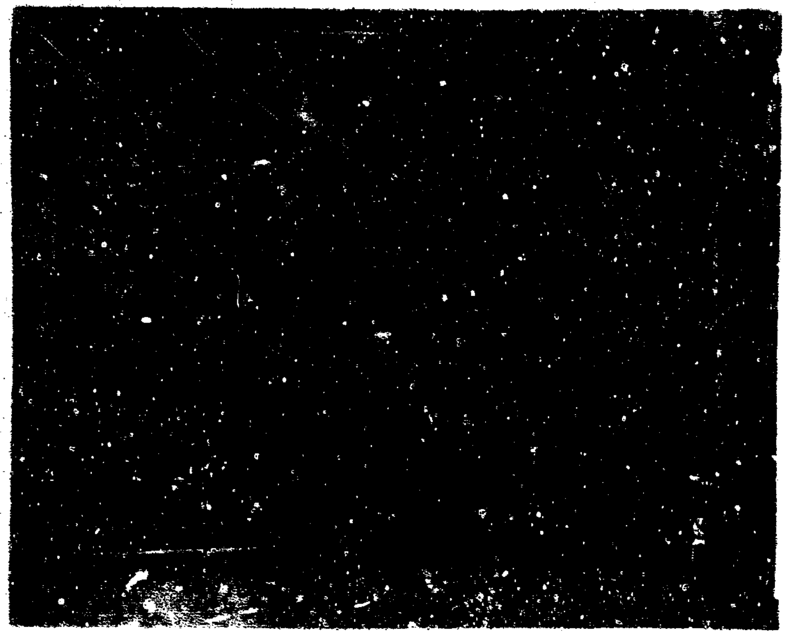


Figure 2. Valve Driver Circuit



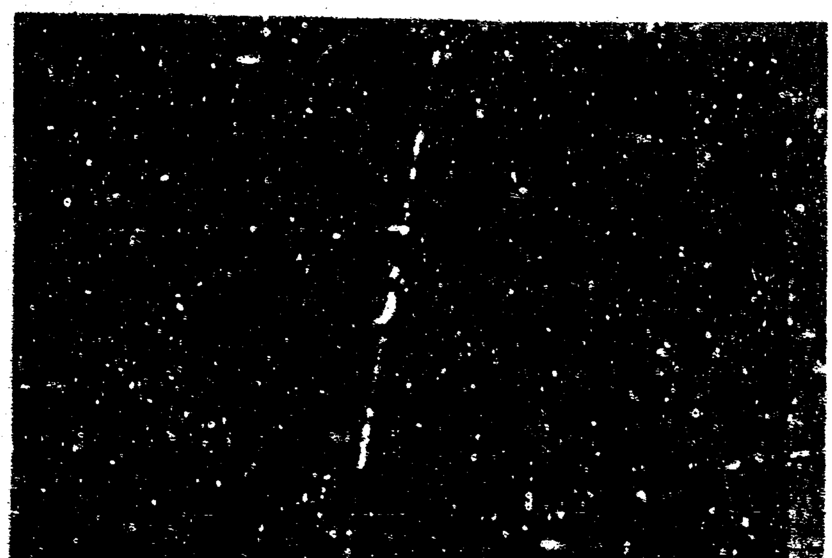
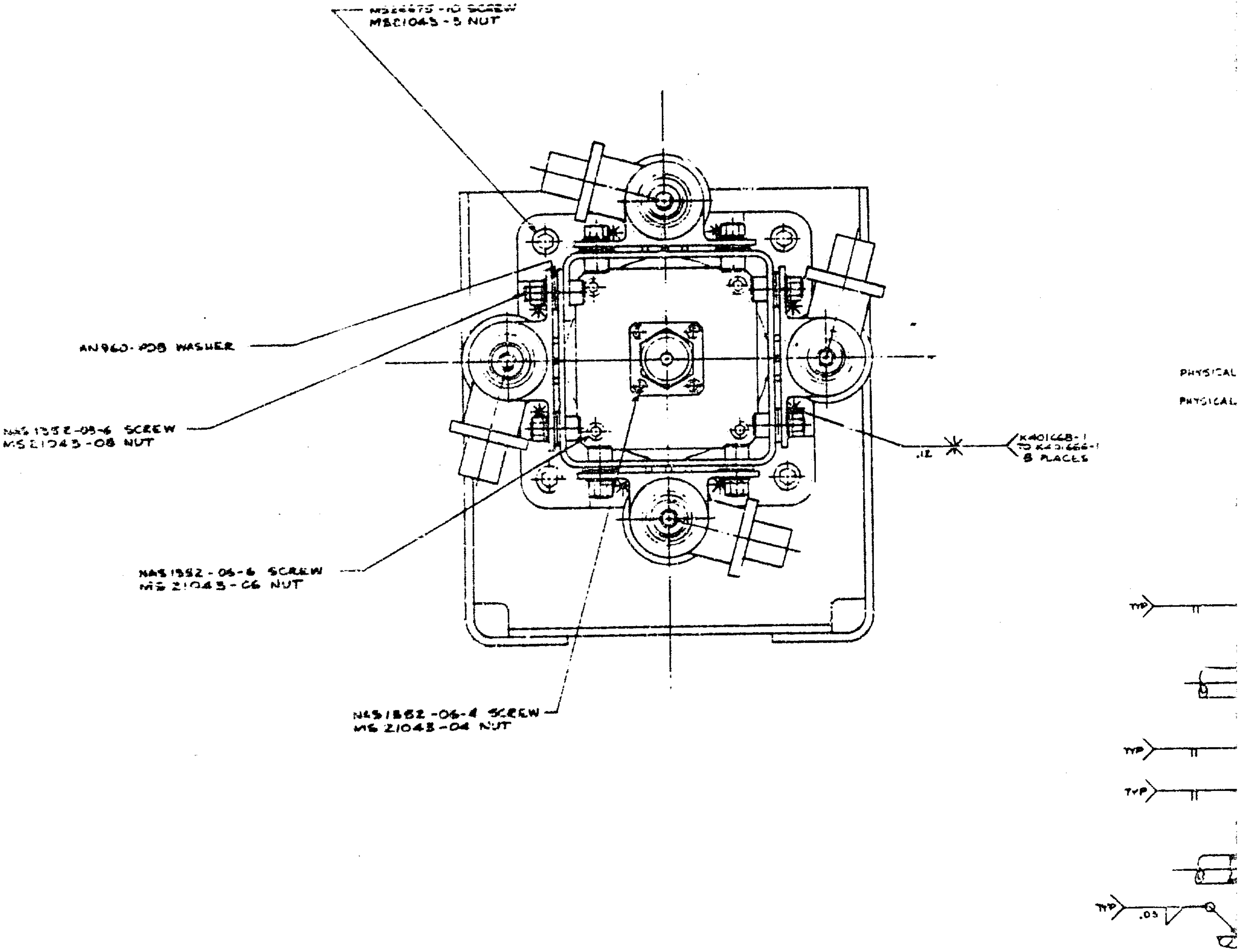


Figure 3. Single-Axis Controller and Valve Driver

be 1550°F. The thruster duty cycle and pulse duration were determined by the ACSKS mission analysis. The minimum propellant temperature of 1500°F was established experimentally as the lowest temperature at which propellant flow tube materials had sufficient catalytic activity to result in nearly complete ammonia decomposition.

During the course of the ACSKS program, a total of three different thrusters were used. The basic design concept of each of the thrusters was the same; however, the implementation of the concept was different for each thruster. The reasons for the differences are explained in Section 5. The design analysis of the thruster concept is reported in detail in Reference 1.

The first thruster used in the life test was the one fabricated for the ACSKS demonstration test. An assembly drawing of the thruster is shown in Figure 4. The detail drawings of the thruster are in Reference 1. This thruster had a solid nickel-200 core on which were wrapped two tubular swaged heater elements. The heater elements had an outer sheath of Inconel 600, magnesium oxide insulation, and a resistance element wire of Kanthal N. Two elements were used for redundancy. The propellant flow tubes, one for each nozzle, were coiled on the core directly over the heater elements. The flow tubes were the catalytic surface on which the ammonia decomposed. The propellant flow tubes were fabricated from type 304 stainless steel, and were sized so that the ammonia decomposition process within them was diffusion controlled. In a diffusion controlled process, the decomposition rate of the ammonia is controlled by the rate at which the reactant, ammonia, diffuses to the flow tube surface and the products, hydrogen and nitrogen, diffuse away, and is not controlled by the reaction rate kinetics at the flow tube surface. The propellant flow tubes and heater elements were secured to the core for structural integrity, and to each other for thermal contact, by brazing. Thermal insulation of the thruster core assembly was achieved by surrounding the core with alternate layers of 0.00025-inch-thick molybdenum foil and 0.010-inch-thick refrasil cloth. The insulation was applied as a spiral wrap on the cylindrical section of the core and as flat discs on the ends. A photograph of the assembled thruster is shown in Figure 5.


MS24675-10 SCREW
MS21043-5 NUT
AN960-PD8 WASHER
NAS1352-08-6 SCREW
MS21043-08 NUT
NAS1352-06-6 SCREW
MS21043-06 NUT
NAS1352-06-4 SCREW
MS21043-04 NUT
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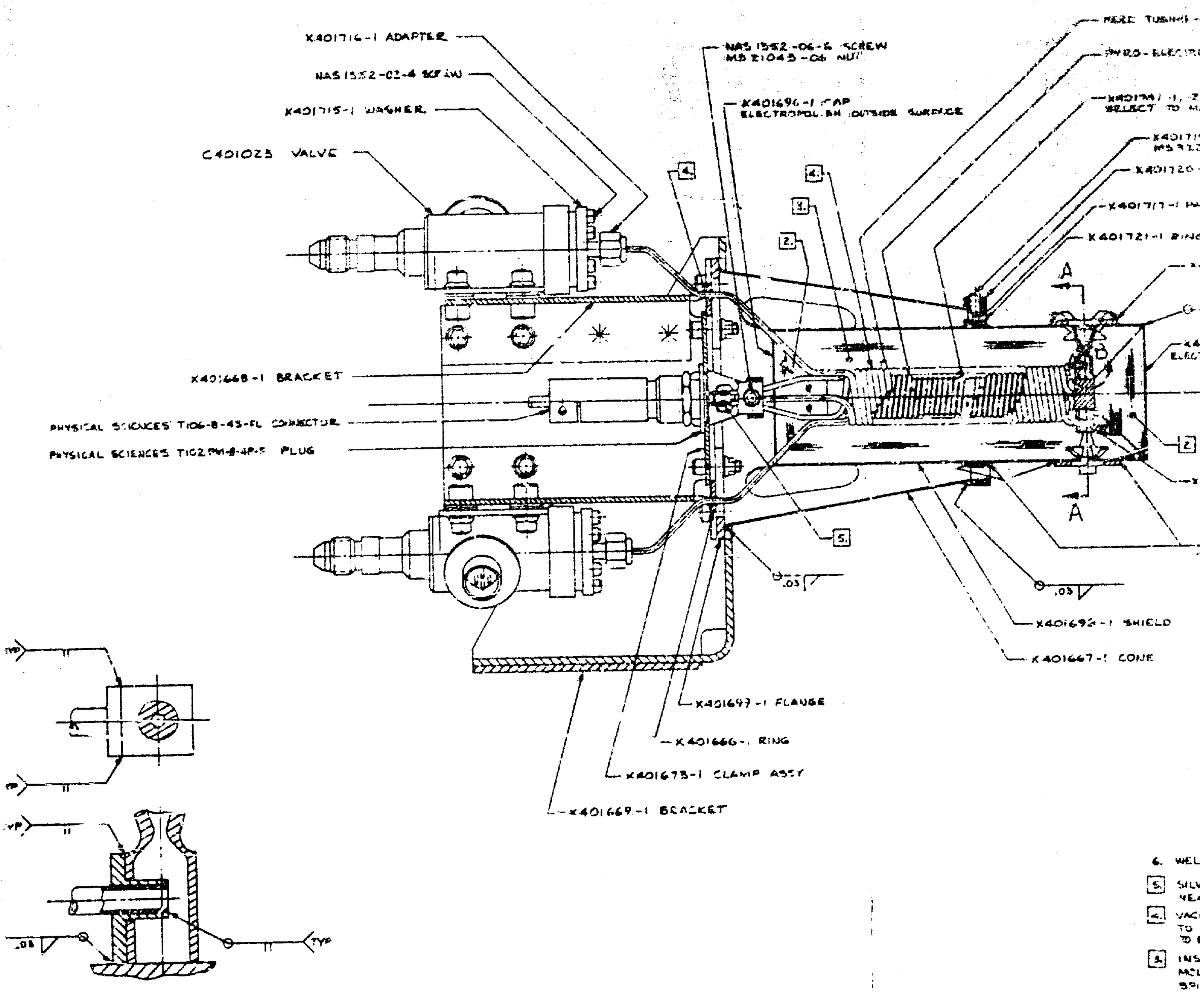

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SCALE 10/1

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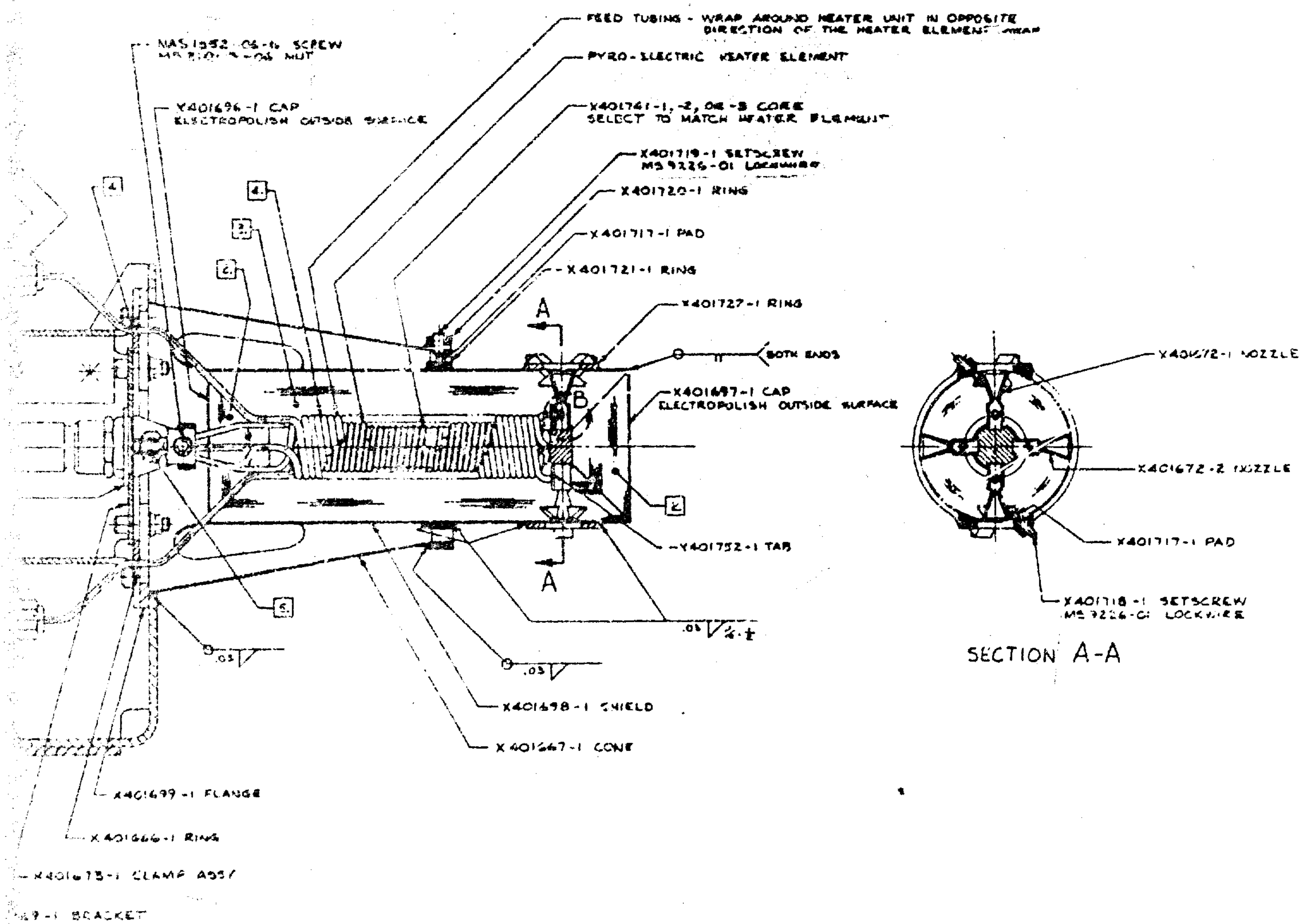


6. WELD PER TRW SYSTEMS SPEC PR 8-1

[5.] SILVER BRAZE CONNECTOR PINS TO HEATER ELEMENTS

[4.] VACUUM BRAZE TUBING TO HEATER ELEMENTS, HEATER ELEMENTS TO CORE, AND TUBING TO RING IN ONE OPERATION. FILLER METAL TO BE AMI-102 (15.2% CR, 8.0% SI, NI BALANCE) ALLOY METALS INC. OR EQUIV.

[3.] INSULATION IS MADE UP OF ALTERNATE LAYERS OF MOLYBDENUM FOIL AND REFRASIL MATERIAL SPIRALLY WRAPPED - APPROX 25 LAYERS OF EACH

[2.] INSULATION IS MADE UP OF ALTERNATE LAYERS OF MOLYBDENUM FOIL AND REFRASIL MATERIAL. APPROX 32 LAYERS OF EACH

1. IDENTIFICATION MARKING IN ACCORDANCE WITH TRW SYSTEMS SPEC. PR 10-1 TYPE 1 CLASS 2 PART NUMBER

NOTES: UNLESS OTHERWISE SPECIFIED

Figure 4. Thruster Assembly, ACSKS -1

C

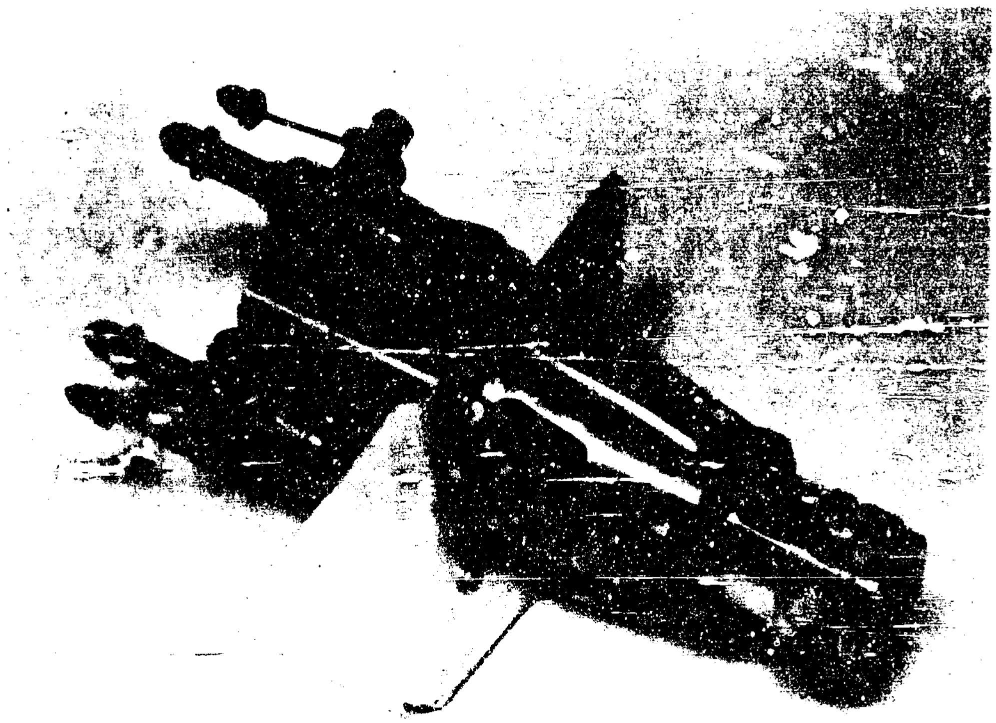


Figure 5. Assembled Thruster, ACSKS

The outer envelope and insulation of the second ACSKS thruster were identical to the first; however, the thruster core assembly was completely redesigned. The heater element used for this thruster is of the cartridge type. A photograph of the element is shown in Figure 6. The cartridge element had an outer sheath of Inconel 600, magnesium oxide insulation, and a resistance element of Nichrome V. The basic element is 3/8-inch in diameter and 3 inches long, with a sheath thickness of 0.040 inch. A 0.075-inch-thick layer of nickel was electroplated on the outer surface of the element sheath. The propellant flow tubes were wrapped into grooves that were machined in the plated layer. The flow tubes were fabricated of nickel 200 with an outside diameter of 0.063 inch and a 0.007-inch wall. A 0.075-inch-thick nickel layer was then electroplated over the flow tubes. The outer surface of the plating was machined to remove the major portion of the plating ridges resulting from the flow tube impressions. The outer diameter of the machined core was 0.645 inch. A nozzle-base ring was welded onto the element sheath. This ring formed the juncture between the flow tubes and nozzle chambers. Both the nozzle-base ring and nozzles were fabricated from nickel 200.

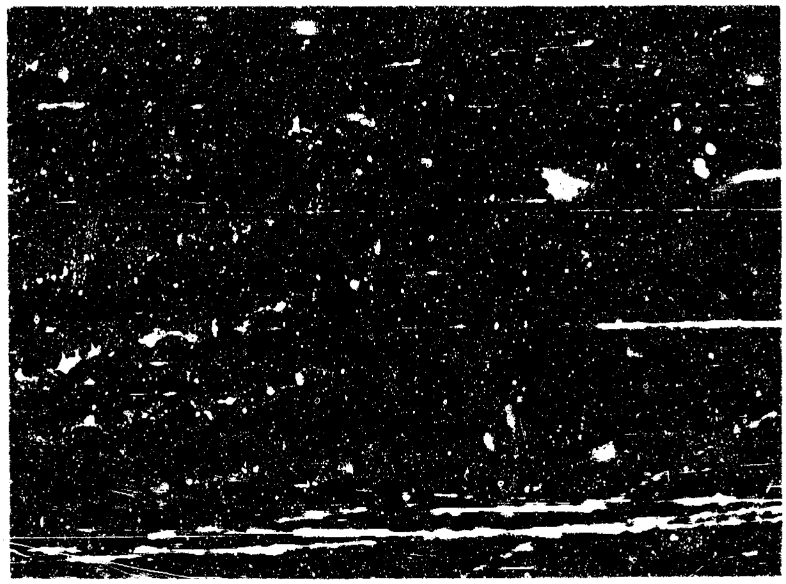


Figure 6. Cartridge Heater Element

The seals between the flow tubes, ring, and nozzle chamber were made by TIG welding. The nozzle configuration of this thruster was the same as that of the original thruster, except that the outer cross-section of the nozzle chamber was cylindrical. A photograph of the thruster core, instrumented with three thermocouples for the thermal loss test, is shown in Figure 7. During the final plating operation on the thruster in which the flow tubes were plated in place, the magnesium oxide insulation of the heater element became impregnated with plating solution. This caused the element wire to develop an internal short. The heater element was machined out of the case and a new cartridge element was pressed in place.

A third thruster was designed, fabricated and tested during the final stage of the life test phase of the ACSKS program. The envelope, support, and insulation of this thruster were the same as those of the first design. This thruster, like the second one, had a completely redesigned core assembly. The thruster used a cartridge heater element identical to that of the second thruster. The heater element was inserted into a machined core on which the propellant flow tubes had been wrapped and the nozzles welded. A drawing of the core is shown in Figure 8, and flow tube retaining ring in Figure 9. It is fabricated of Inconel X750. The flow tubes used on this thruster were fabricated as a composite. These tubes

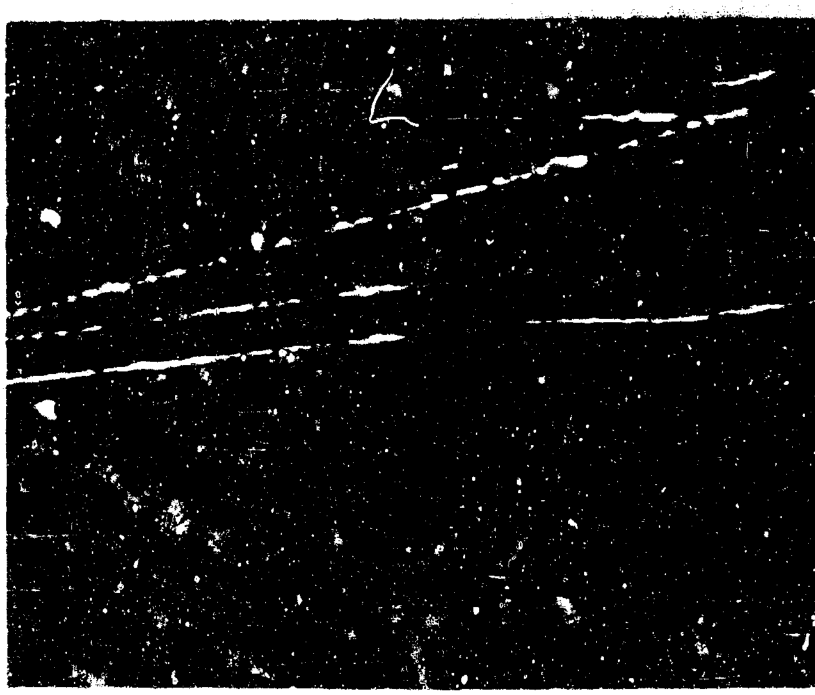


Figure 7. Thruster Core Assembly, ACSKS-2

were formed by plasma spraying a 0.0015 ±0.0005-inch layer of alumina on nickel 200 tube that had a 0.063-inch external diameter and a 0.007-inch wall. The plasma-sprayed tube was inserted into an Inconel X750 tube that had a 0.078-inch outside diameter and a 0.005-inch wall. The outer tube was then compressed against the inner plasma-sprayed tube by a drawing operation. The rationale for this type of propellant flow tube is explained in Section 5.3.

The nozzles of this third thruster were modified versions of those used on the first thruster. The modification included increasing the wall thickness in the region of the nozzle throat and changing the material from nickel 200 to Inconel X750. The thicker wall section of the nozzle increased its load carrying capability. The nozzles were designed to support the thruster core during the launch environment. The material of construction change was made to obtain uniformity of structural material composition. A drawing of the nozzles is shown in Figure 10. During thermal performance testing of the thruster, a tenacious, high-emissivity oxide coating formed on the nozzle surfaces. This resulted in a large thermal loss from the thruster. To correct this, the conical expansion and throat

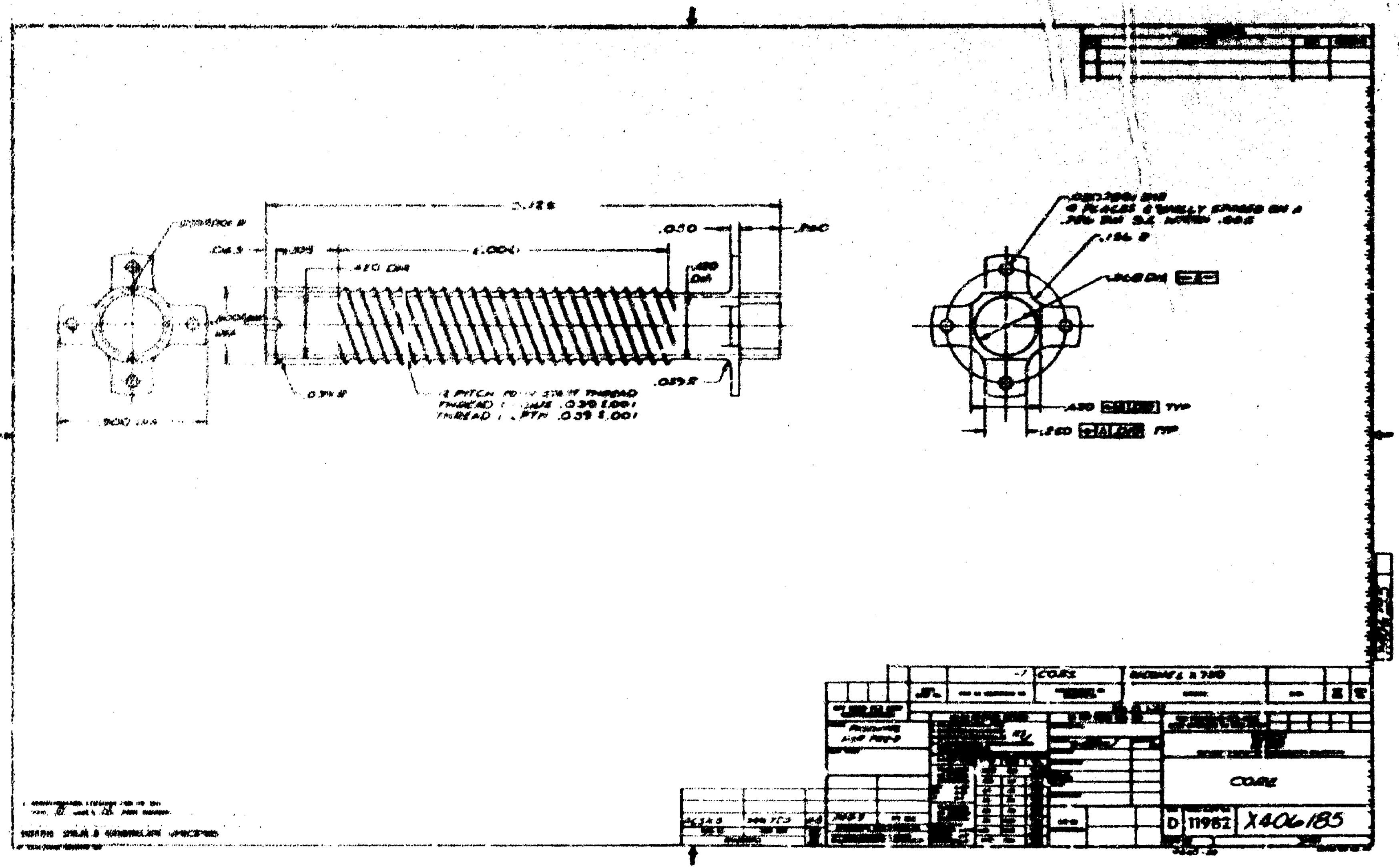


Figure 8. Thruster Core, ACSKS-3

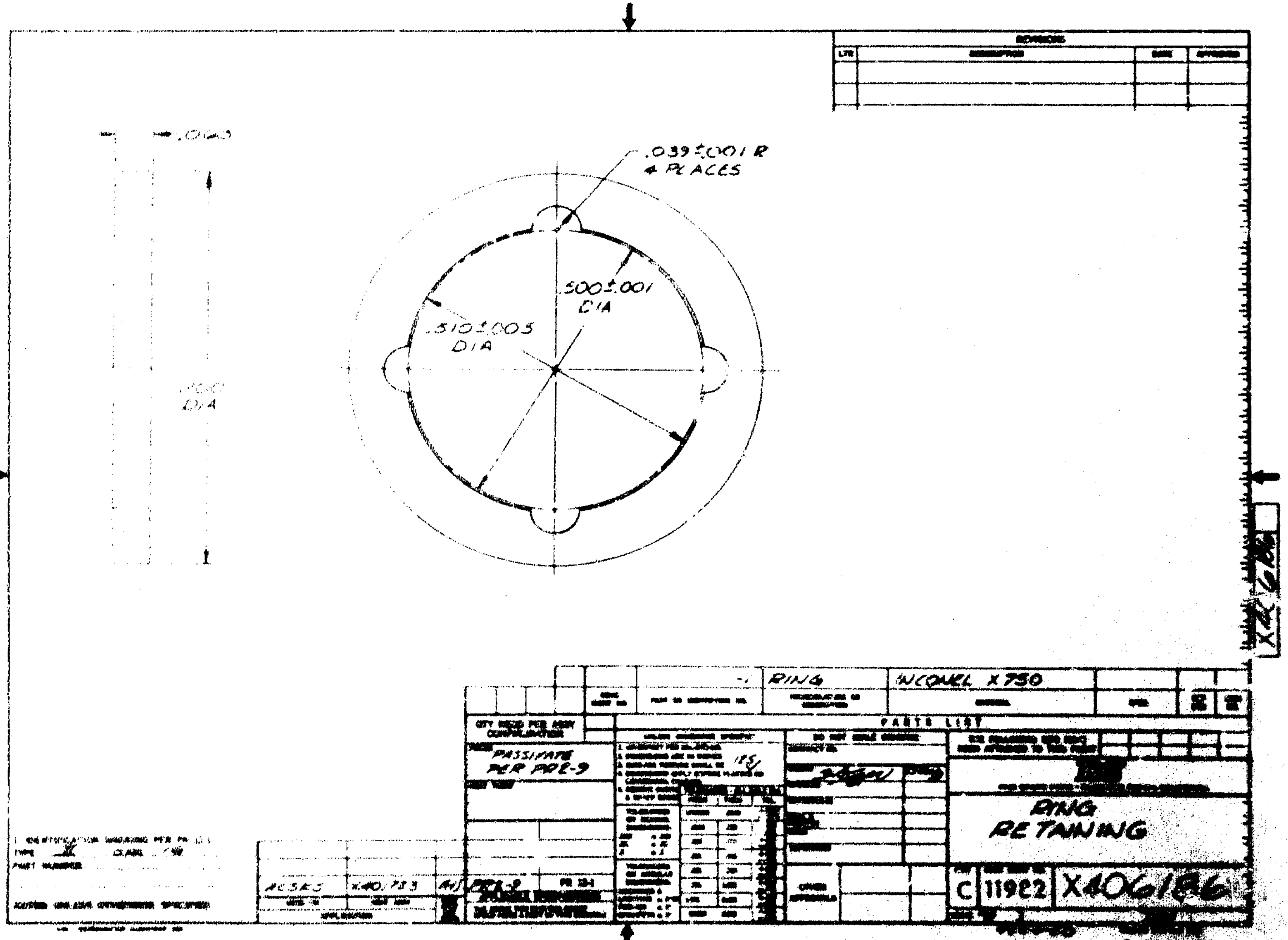


Figure 9. Ring, Retaining

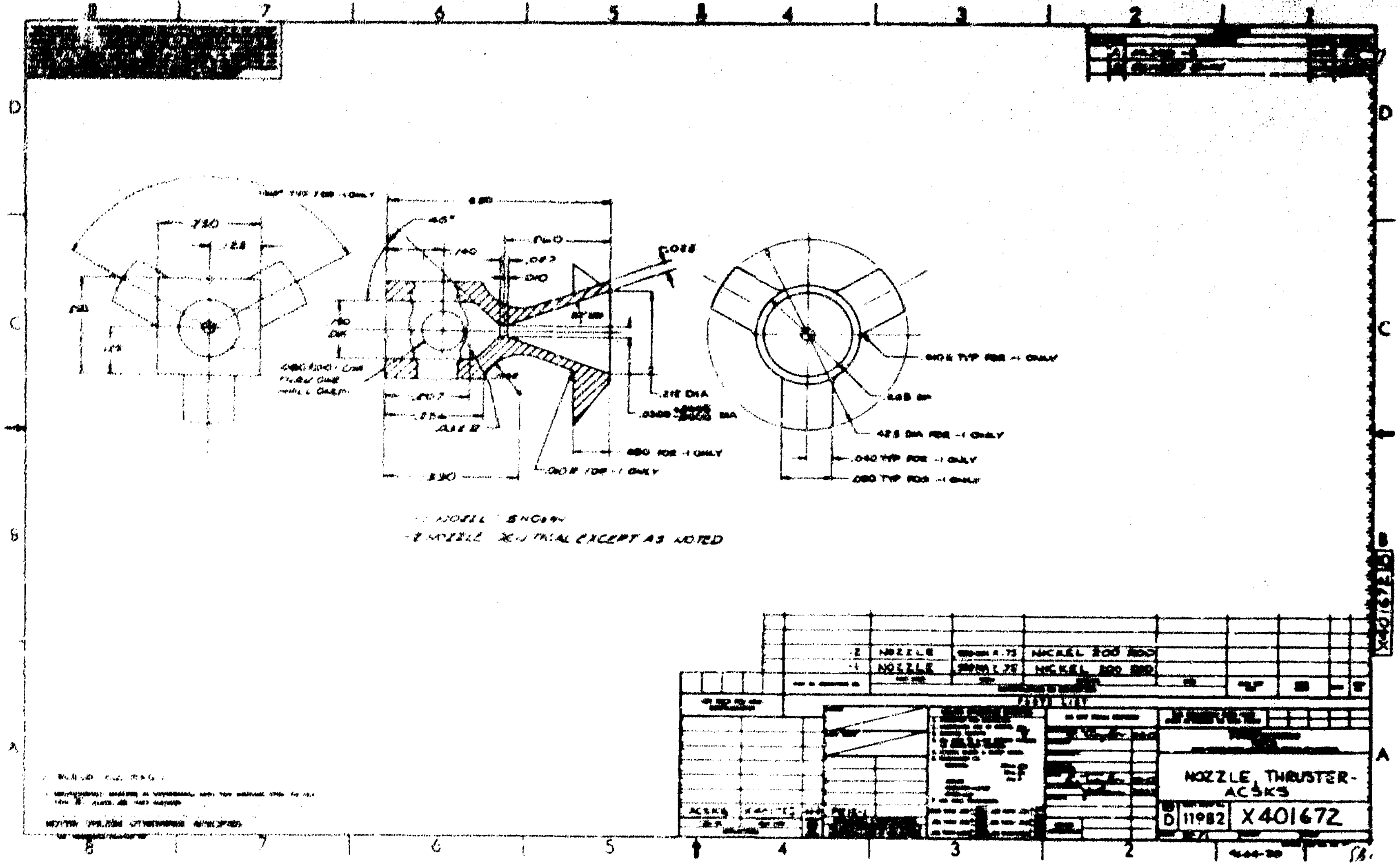


Figure 10. Nozzle, Thruster, ACSKS -3

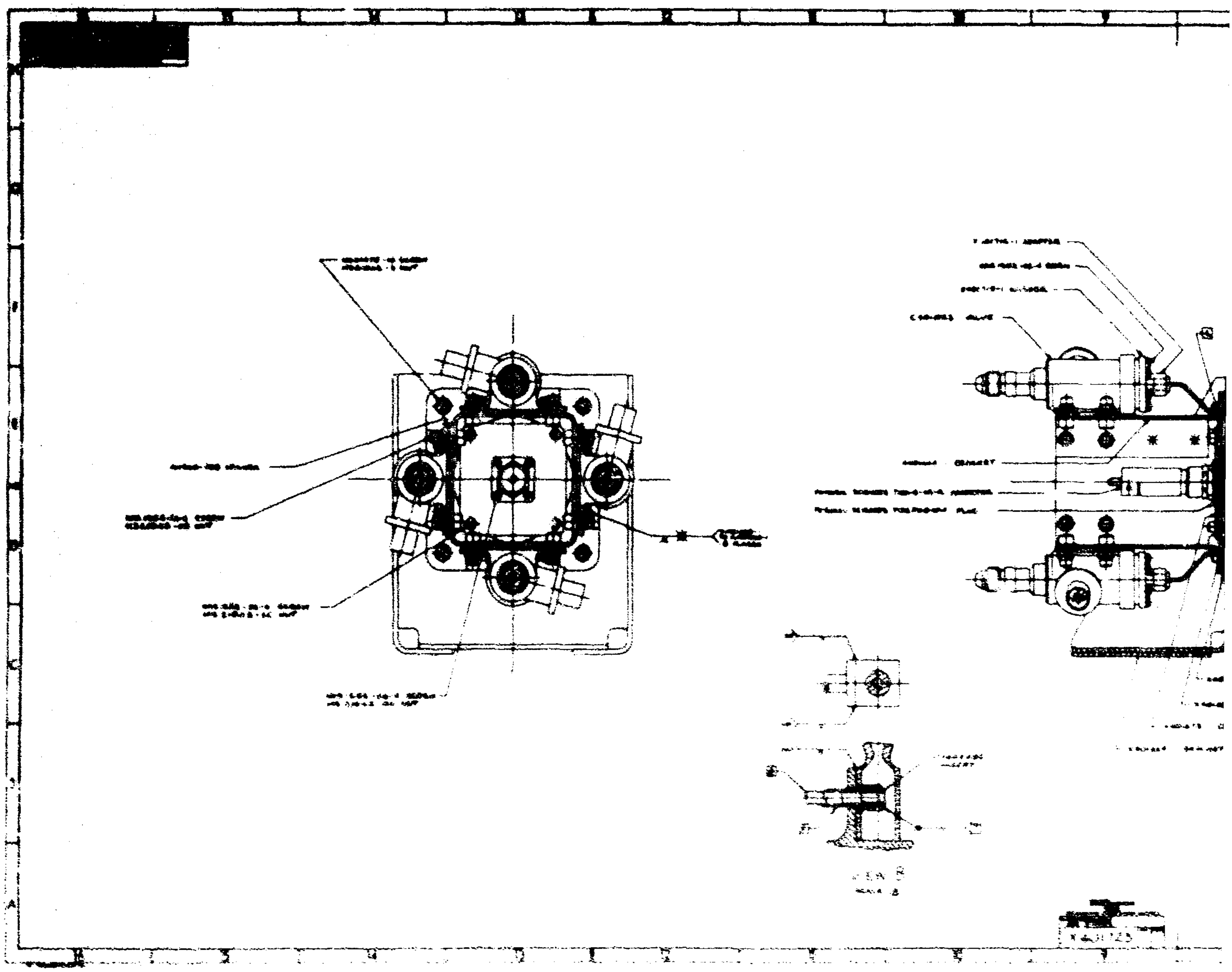
sections of the nozzles were removed and replaced with nickel 200 sections. The junction between the nickel expansion and throat section and the Inconel chamber section was made by TIG welding with nickel filler material.

The flow tubes were terminated on the thruster core by TIG welding to a tab that was an integral part of the core. This core tab formed a portion of the nozzle chamber. A detail of this assembly is shown in Figure 11. The chamber section of the nozzle was TIG welded to the core and core tab. No filler material was required. The propellant flow tubes were attached to the core with a plasma sprayed Inconel 600 powder. During the thermal performance tests in which the nozzles oxidized, an oxide film formed on the plasma-sprayed surface of the thruster core. Because it was not possible to eliminate this oxide formation, which had a relatively high thermal emissivity, the exposed surface of the thruster core was nickel plated by chemical vapor deposition. This was accomplished by heating the thruster core in an atmosphere of nickel carbonyl. The thickness of the nickel layer was 0.0018 inch.

This third ACSKS thruster was the one used in the final six month test period of the program. It was part of the deliverable items at the end of the test period. The other two thrusters were disassembled and subjected to both chemical and metallographic examination.

3.3 FEED SYSTEM

The ACSKS ammonia feed system used in the life test was the same one designed and assembled for the demonstration test phase of the program. The feed system for the complete attitude control and station keeping subsystem consists of two propellant storage tanks, each with a propellant supply unit. Each tank contains one-half of the total propellant required for the mission and each supply unit has the capability of supplying the maximum propellant flow rate that occurs during the spacecraft acquisition mode. These values, as determined in Reference 1, are a total propellant capacity of 44 pounds and a maximum flow rate of 4×10^{-4} lb/sec. The feed system designed for the demonstration test was a half unit of the total spacecraft system.



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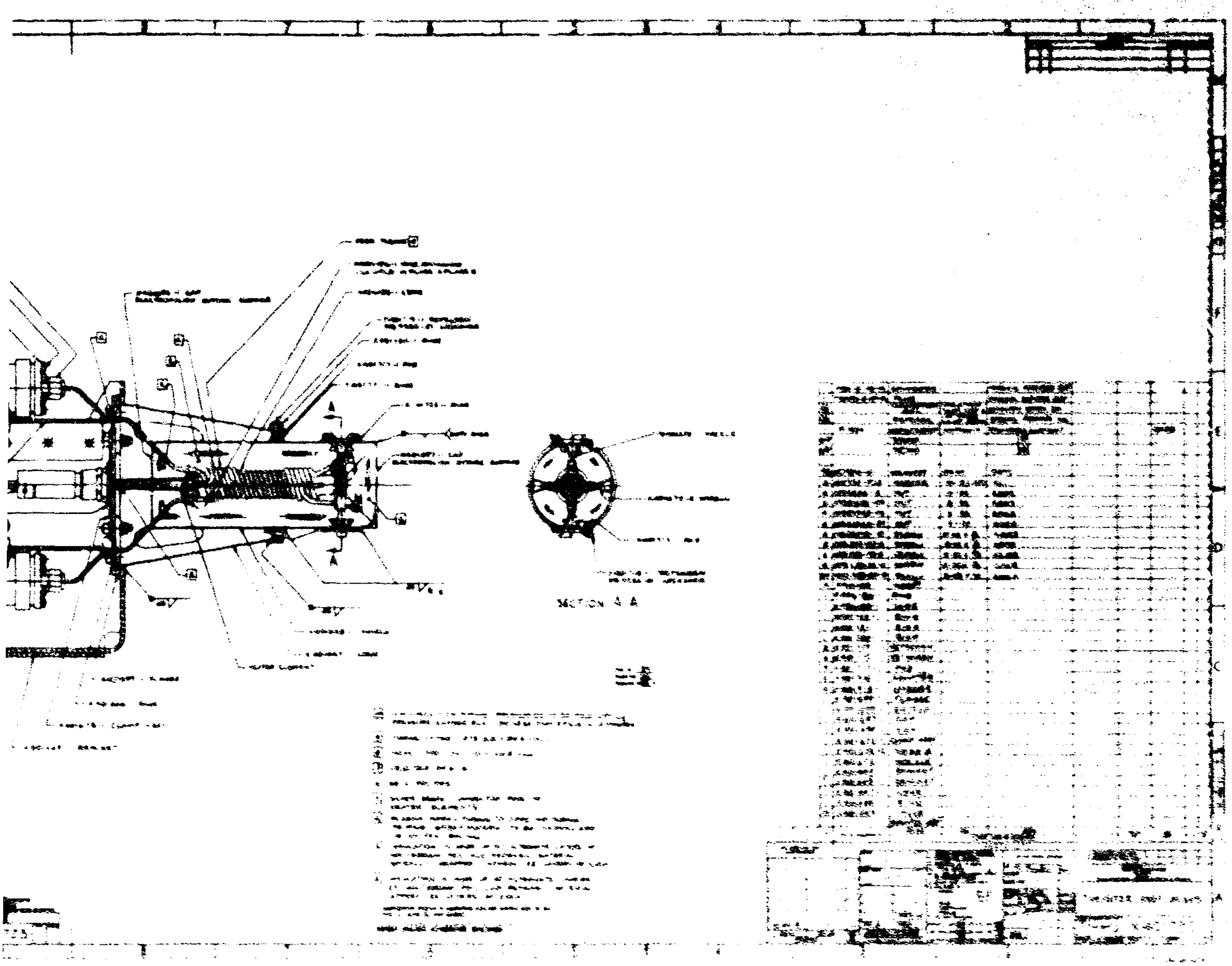

Figure 11. Thruster Assembly, ACSKS -3

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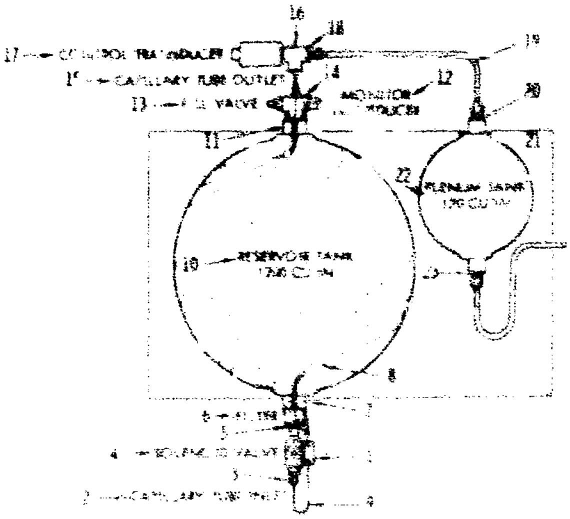


Figure 12. ACSKS Feed System Schematic

The feed system was designed to operate in a zero gravity environment. It utilized capillary tubes for flow regulation and vaporization. The design analysis and description of the feed system components are in Reference 1. A schematic of the feed system is shown in Figure 12 and a photograph of the system in Figure 13. The feed system components are identified in Table [illegible]. A schematic of the [illegible] and switch is shown in Figure [illegible].

3.[illegible] OVERALL TEST SYSTEM

The complete system used in the integrated test [illegible] schematic form in Figure 15 and a layout with the actual [illegible] Figure 16. The units in test, the control electronics, thruster and feed system, were located in vacuum chambers. The thruster and [illegible] were located in a [illegible] right-cylinder vacuum chamber [illegible] The vacuum was maintained [illegible]

[illegible]

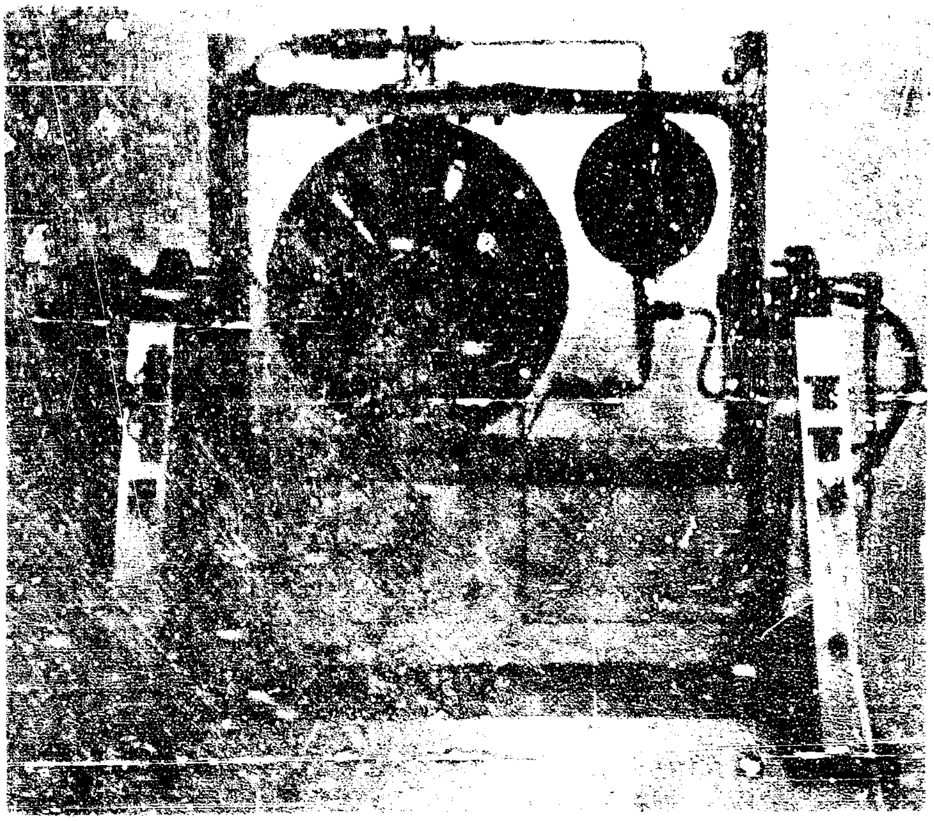


Figure 13 ASKS Feed System

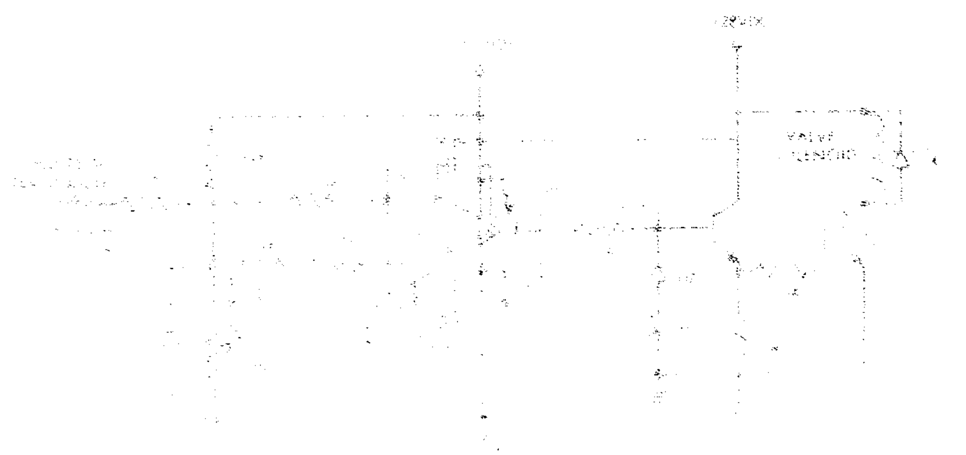


Table 1. Ammonia Feed System Component Identification

No.	Component Name
1	External Tube Heater Support Plate
2	Capillary Tube Inlet Fitting
3	Valve Void Reducer
4	Control Valve
5	Valve Filter Adapter
6	Microporous Filter
7	Boss No. 1, Reservoir Tank
8	Eccobond® [illegible] Epoxy
9	Capillary Tubes and Solder
10	Reservoir Tank
11	Boss No. 2, Reservoir Tank
12	Monitor Transducer
13	Fill Valve
14	Fill Valve Fitting
15	Capillary Tube Outlet Fitting
16	Control Tee
17	Control Transducer
18	Control Tee Outlet Union
19	Reservoir—Plenum Connecting Line
20	Plenum Inlet Union
21	Boss No. 1, Plenum Tank
22	Plenum Tank
23	Plenum Outlet Union

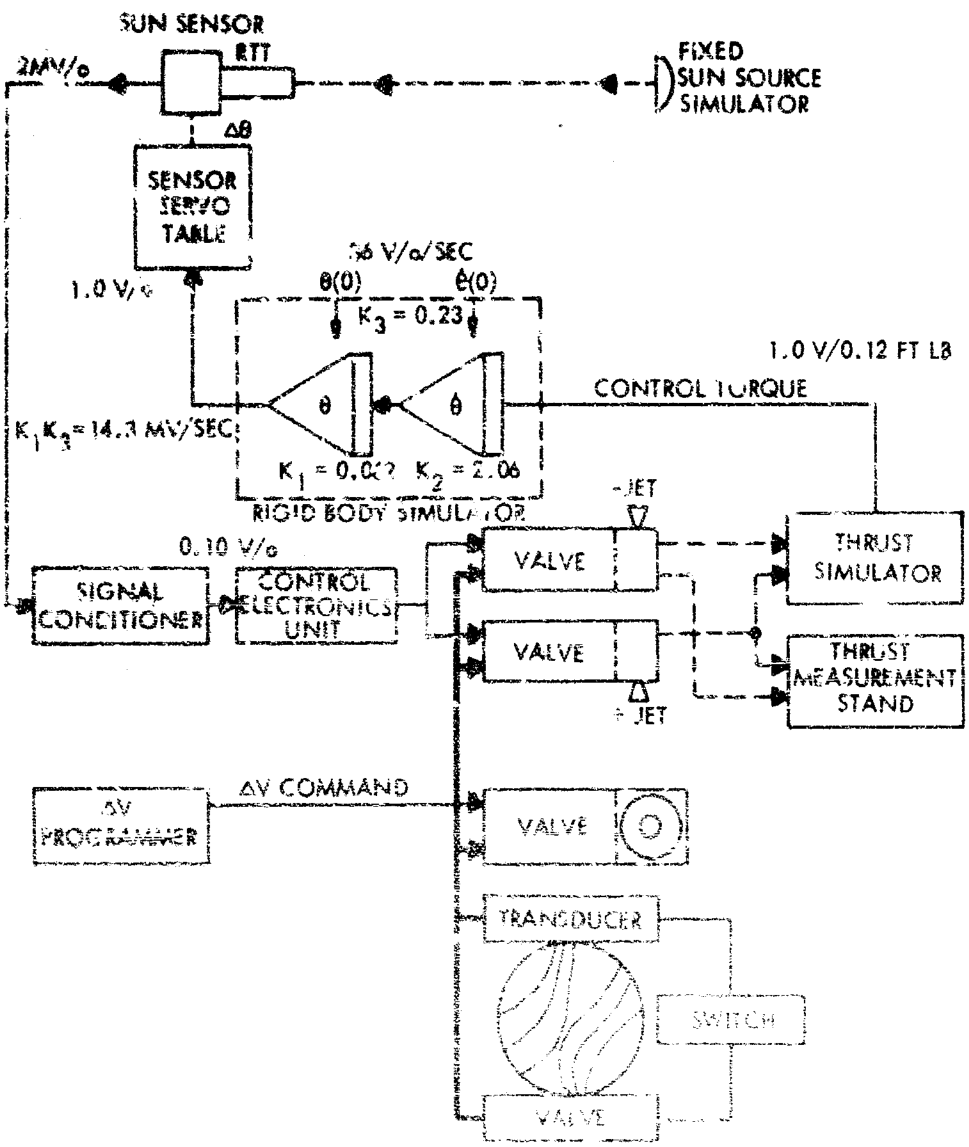


Figure [illegible] - Test Block Diagram

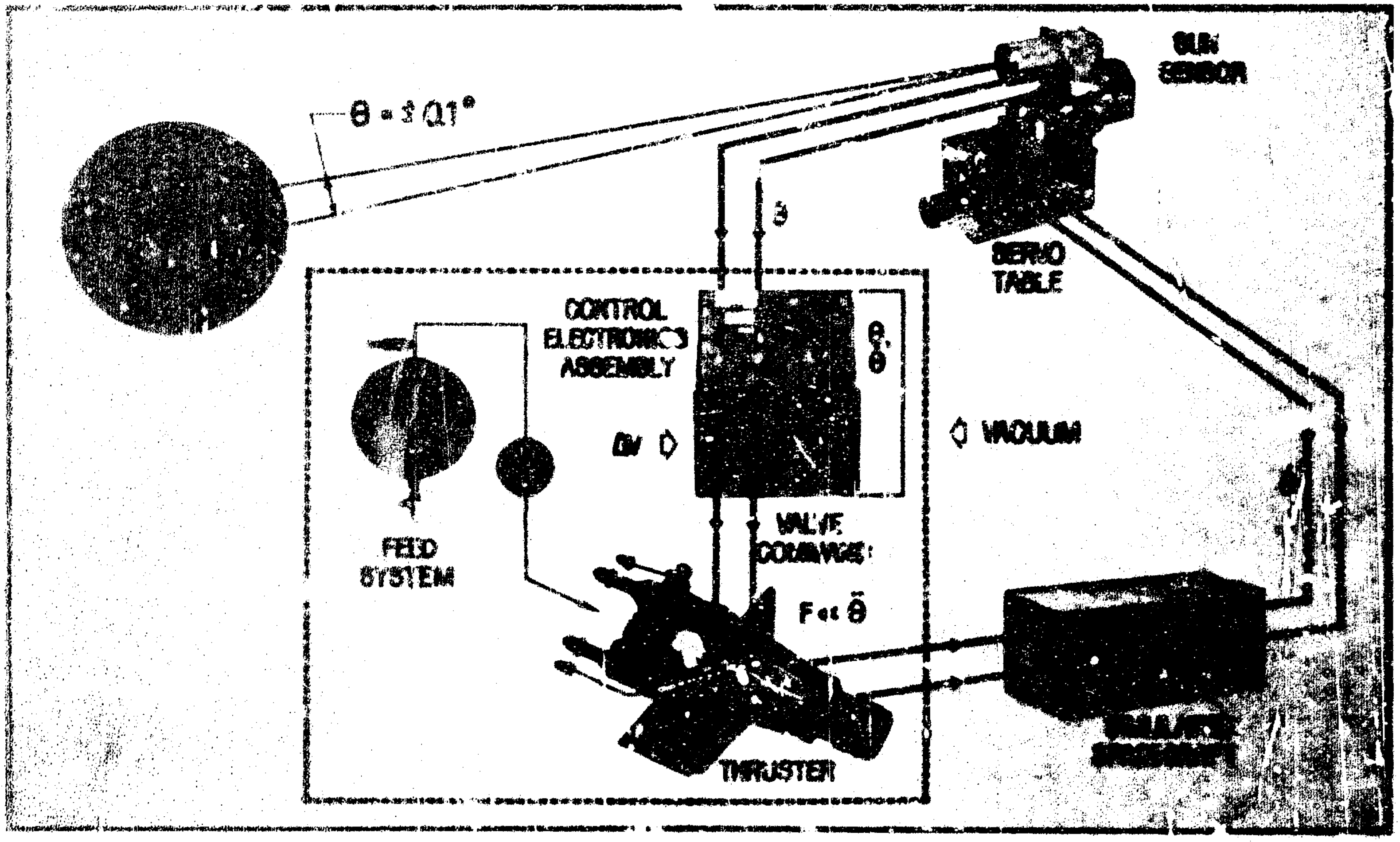


Figure 16. Integrated Test Layout

temperatures. The thruster exhaust at these periods is essentially pure ammonia. The ammonia environment in the tank might have had a detrimental effect on the electronic components.

The OGO sun sensor-stimulus and the rigid body simulator were located outside of the vacuum chamber. Photographs of the test system are shown in Figures 17 and 18. Both the sun sensor and rigid body simulator were replaced with a pulsing circuit during the latter portion of the life test.

3.5 TEST OPERATION

The test was designed to simulate both spacecraft normal mode attitude control and station keeping. Two of the thruster's four nozzles were used in normal mode operation. The propellant pulses from one nozzle produced a positive command torque on the simulated spacecraft and the other a negative torque. The input signal to the valve driver circuits of these two nozzles was used as the electric analog of the impulse bit produced during the propellant pulse. This electrical signal was input to the rigid body simulator which simulated the inertial properties of a spacecraft. The simulator was essentially a pair of integrating circuits in series. The first would convert the impulse bit into a signal that represented an acceleration of the spacecraft. The second integrator converted the acceleration signal into a spacecraft position signal. This signal was used to activate the motor drive of the sun sensor. The sun sensor was pointed at a fixed light source. The electrical output of the sun sensor electronics was proportional to the angle between the sensor and light source. This electrical output was the input error signal to the control electronics. By virtue of the lead-lag network in the feedback loop of first stage amplifier in the control electronics, the error signal in the control electronics is due to both the angular position and rate of change of position of the sun sensor with respect to the light source. The magnitude of this error signal controlled the activation of the thruster propellant flow control valves. The pointing accuracy or deadband control limits of the sun sensor was maintained at ±0.1 degree. The normal mode control command thruster pulse duration was 50 milliseconds. The time averaged pulse frequency was set at one per minute (by adjusting the spacecraft inertial properties in the rigid body simulator).

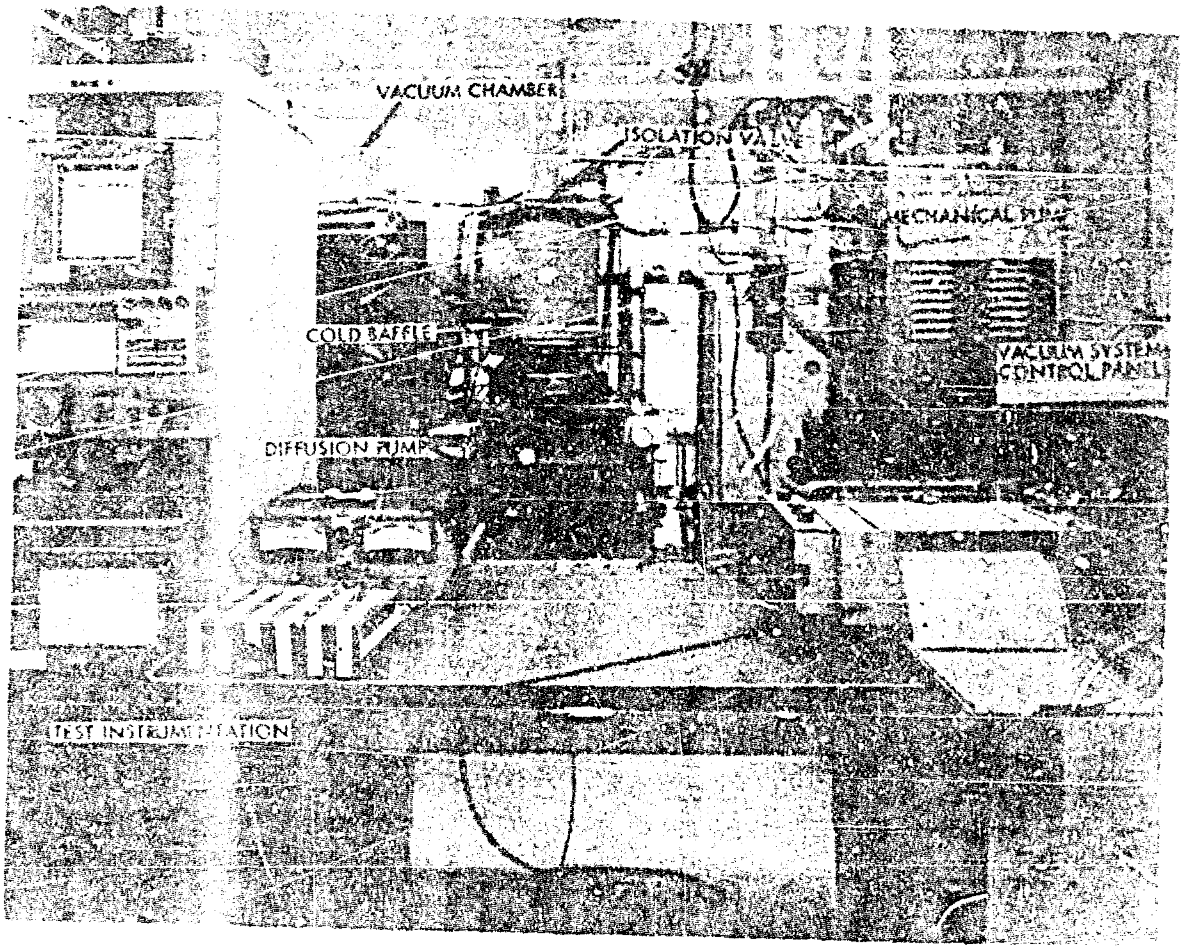


Figure 17. Demonstration Test System, Front View

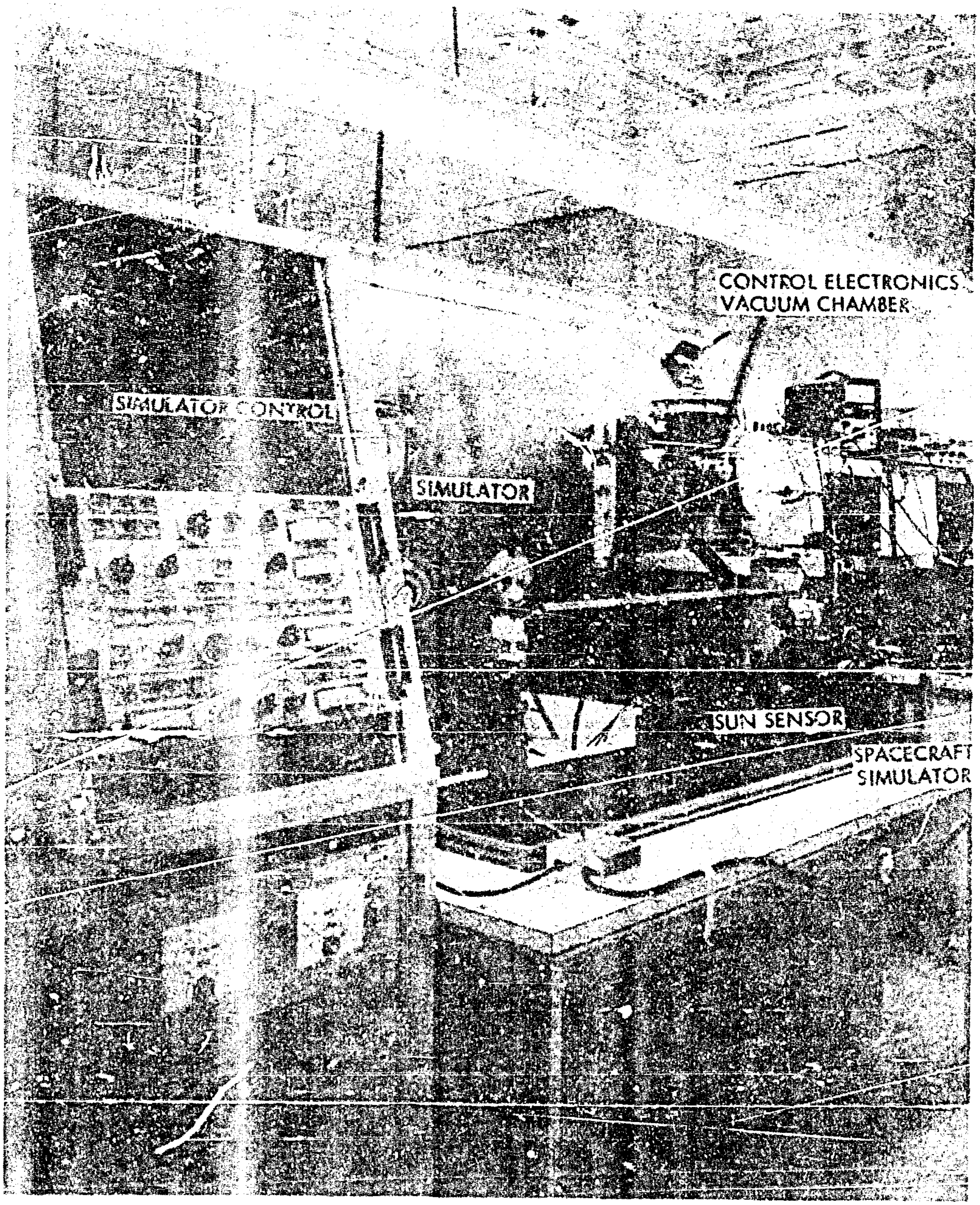


Figure 18. Demonstration Test System, Side View

After 682 days of the life tests, the rigid body simulator and sun sensor were replaced with a pulsing circuit. The sun sensor was not able to track the output of the rigid body simulator due to excessive wear of the sensor drive gear. This non-tracking resulted in a high and erratic command pulse frequency from the control electronics. Because there was insufficient time to overhaul the drive train of the sun sensor, the pulsing circuit was substituted. This pulsing circuit produced an error signal in the final stage of the control electronics that would result in a valve pulse command. The frequency of the pulses were adjusted so that an alternate positive and negative pulse would be commanded at 1-minute intervals. A schematic of the test system with the pulsing unit is shown in Figure 19.

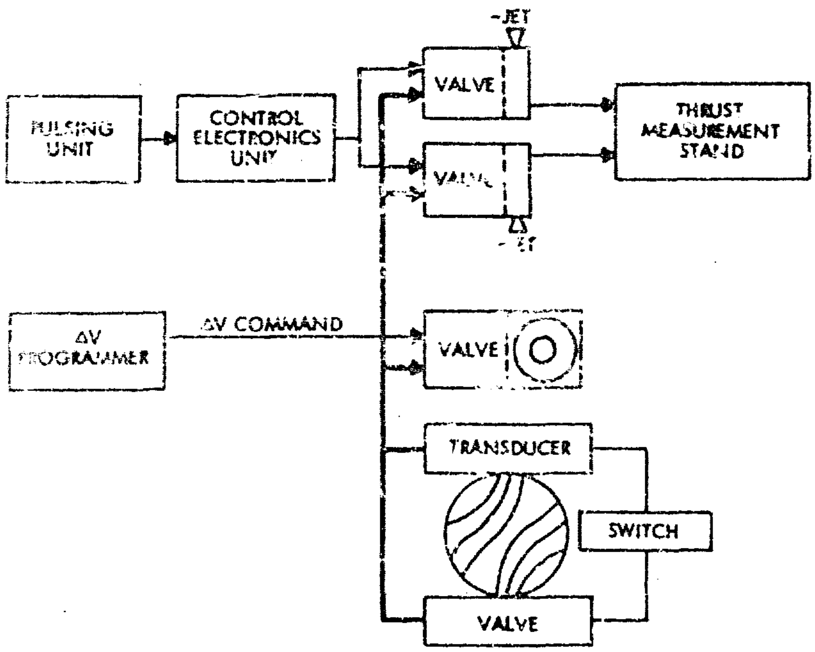


Figure 19. Test Block Diagram, Pulsing Circuit

The ΔV or station keeping mode was simulated by pulsing propellant through a third thruster nozzle. This was accomplished with a pulse-time circuit. The pulse duration was 1 second and the frequency was one pulse per 50 seconds, corresponding to a 2 percent duty cycle. Although the thruster had the capability of sustaining longer pulses, the vacuum system could not. During propellant pulses of greater than 1-second duration, the pressure in the vacuum chamber would exceed the maximum for operation of the diffusion pumps. Sufficient ΔV mode operation was performed to result in a total propellant expenditure of 100 lb-sec per month. The fourth nozzle of the thruster was inoperative during the test period.

Operating characteristics of the control electronics were monitored by observing the position of the sun sensor. This was done by monitoring both the output of the sun sensor directly and also the output of the position integrator of the rigid body simulator. Phase plane plots of the closed-loop operation were generated by tracing the output of the position integrator against the output of the rate integrator in the rigid body simulator. This could be done without interrupting closed loop operation.

Thermal performance of the thruster was measured by monitoring the voltage across the thruster heater element, the current in the heater circuit, and the thruster temperature. Thruster temperature was measured with thermocouples located along the core and at the base of the nozzle chamber. The core temperature of the thruster that had the Kanthal N element was also monitored from the element resistance. This method proved to be more reliable than with thermocouples.

The thruster was attached to a thrust and impulse stand during the test. A photograph of the thruster and stand is shown in Figure 20. In order to measure thrust and specific impulse during the test, it was necessary to decouple the thruster from the closed-loop operation. The thrust stand operated on the same principle as a ballastic galvonometer, and its rate of movement resulting from a thruster pulse produced an output voltage. The magnitude of the output voltage was proportional to the impulse bit generated during the propellant pulse. The time rate of change of the stand output voltage was proportional to the instantaneous thrust force generated by the thruster. The mass of propellant expelled during a performance monitoring pulse was determined by measuring the pressure drop in a calibrated volume located in a section of the propellant feed line. When thruster performance measurements were being made, the valve pulses were generated by triggering the valve driver of the control electronics with an external source.

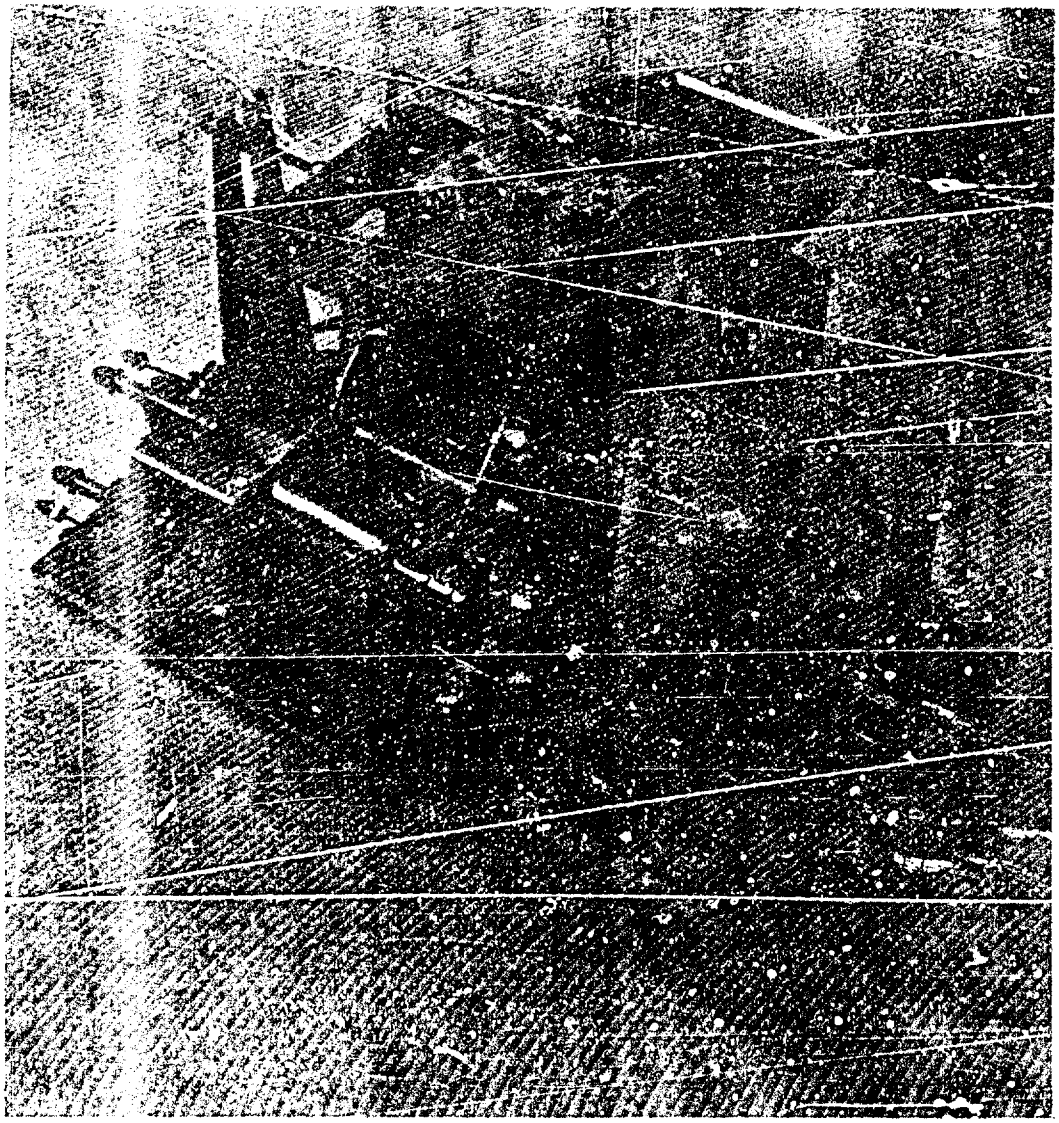


Figure 20. Thruster — Test Stand Unit

The performance characteristics of the amonia feed system were determined by monitoring the pressure of the propellant delivered to the thruster. In order to monitor its control characteristics under high flow demand for extended periods, it was necessary to bypass the thruster and expel propellant through a flowmeter. This was done, however, without decoupling the system from closed-loop operation. The feed system, as can be seen in Figure 13, was mounted on a frame that could be rotated. It was possible to expel either liquid or vapor phase ammonia from the storage tank by rotating the frame which in turn changed the liquid level with respect to the flow control valve at the entrance to the capillary tubes. The ammonia phase leaving the storage tank could also be changed without decoupling from closed-loop operation.

4. LIFE TEST RESULTS

The entire life test phase of the program extended for a period of 24 months. This started immediately following the conclusion of the one-month demonstration test. The historical sequence of the life test is depicted on the bar graph in Figure 21. The life test, with all of the original units of the demonstration test, started on 7 August 1967. This first test period continued through 11 December 1967. The units had logged 154 days of operation up to that time. The test was interrupted in December because of severe degradation in thruster specific impulse performance. The control electronics and feed system, as well as the rest of the test system, were secured in a stand-by condition and the thruster was disassembled for inspection. The results of the inspection indicated that the propellant flow tubes had undergone a catastrophic attack by the ammonia propellant. Following the initial visual inspection, the thruster was subjected to a chemical and metallographical examination. This examination and the results are discussed in Section 5.1.

Fabrication of the second (nickel plated) thruster was started approximately 1 month after the life test was interrupted. Prior to the start of fabrication, data from the examination of the first thruster were analyzed and materials compatibility tests with ammonia were performed. The results of the compatibility tests indicated that nickel was sufficiently resistant to ammonia attack for a 1-year life and had sufficient catalytic activity for use as propellant flow tubes. The 1-year life estimate implied an ammonia exposure time of less than 10 hours. A 50-millisecond pulse every minute for 1 year corresponds to an exposure time of 7.31 hours. Although the nickel tube samples survived continuous exposure to ammonia for more than 80 hours, the one-to-one correlation between intermittant and continuous exposure used in selecting nickel proved to be in error. However, this was not known at the time, and nickel was selected as the flow tube material for the second thruster.

The second ACSKS thruster was incorporated into the life test, and the life test restarted on 22 March 1968. After the initial heat-up in the test, the thruster thermal performance began to steadily degrade. The life test was interrupted on 9 April for the purpose of examining the thruster. The thruster was reinsulated and the life test resumed on

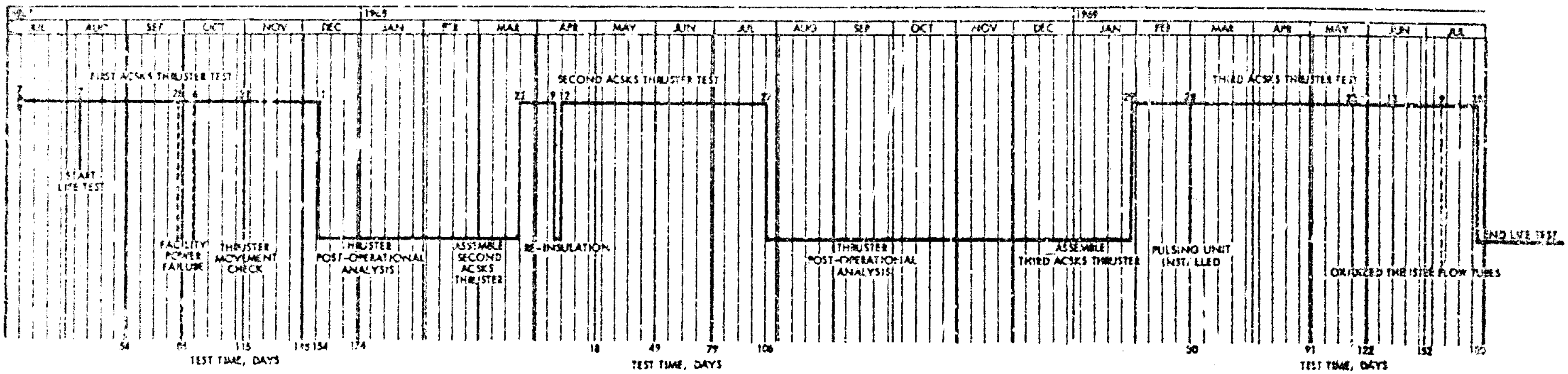


Figure 21. Life Test Operational History

12 April. All units in test were performing within design specification. A problem developed in monitoring the specific impulse performance of the thruster in June 1968. This resulted from building modifications near the test area. These modifications caused vibrations generated by the system's mechanical pump to increase in magnitude in the vicinity of the vacuum tank. The vibration intensity increased the noise level in the thrust balance monitoring readout. A filter circuit was designed and implemented to circumvent this problem. Once the impulse monitoring problem was resolved, the impulse degeneration problem reappeared. The specific impulse performance of the thruster had grossly degraded during the month of July. The life test was again interrupted on 27 July 1968 after 106 days of thruster operation. All other units of the integrated system tests were secured in a stand-by condition and the thruster was removed for inspection. The thruster flow tubes were pressurized with nitrogen for a leak check. The results indicated that the propellant tubes had become porous. The error in the one-to-one exposure time correlation had become evident. This thruster was subjected to a chemical and metallographical examination, as was the first, and the results are discussed in Section 5.2.

Materials compatibility and catalytic activity tests with ammonia had been in progress concurrent with the life tests and were continued into the period following the thruster flow tube failure. Results of the material compatibility tests indicated that rate of ammonia attact on materials such as stainless steel and nickel was not entirely a function of ammonia exposure time during pulsed operation. Total time of the test and duty cycle of the pulsed exposure also have a significant effect. The catalytic activity test results indicated that those structural materials exhibiting good catalytic activity for ammonia decomposition had negligible resistance to ammonia attack. Those materials that had good corrosion resistance to ammonia under thruster operating conditions had negligible catalytic activity for ammonia decomposition. These tests indicated that one way of obtaining both the required resistance to ammonia attack and the required catalytic activity for ammonia decomposition was to use a composite propellant flow tube. The composite tube would have an inner surface that would have the required catalytic activity and an outer layer that would resist ammonia attack and provide structural support.

As a result of this solution to the compatibility problem, the third ACSKS thruster was designed and fabricated. The life test was restarted on 29 January 1969, using the new ACSKS thruster. After approximately 30 days of operation, the drive train wear on the OGO sun sensor had reached a state requiring a complete overhaul before it could be used further in the life test. Thus, the OGO sun sensor was replaced with the pulsing circuit. The life test was continued to 28 July 1969, which was its scheduled termination date. This corresponded to 180 days of continuing operation. All ACSKS units were operating within their design specifications during the final stages of the life test phase.

Both the control electronics and feed system were operated in the integrated test system for a total of 540 days. The feed system was operated for 540 days and charged with ammonia for a continuous period of 755 days. The third ACSKS thruster was held at design operating temperatures and was subjected to propellant pulses for a continuous period of 180 days.

4.1 CONTROL ELECTRONICS TEST RESULTS

The control electronics unit, assembled for the demonstration test, was used throughout the entire testing phase of the ACSKS program. This unit maintained a deadband limit which corresponded to a pointing accuracy of ±0.1 degree. A typical phase plane plot is shown in Figure 22. It was able to maintain this pointing accuracy even as the affects of gear wear in the OGO sensor drive increased. During the period of degradation in the sensor drive, the commanded pulse frequency increased from the nominal 1 per minute to a rate as high as 10 per minute. This change in pulse frequency was due to the erratic movement of the sun sensor head which manifested itself in a high error rate signal in the control electronics.

The electronics control unit did not drift from its nominal control point during the entire time period while under vacuum operation. There was, however, a drift in the set point between operation in air and in vacuum. This drift was traceable to a mismatch in the thermal characteristics of the Field Effect Transistors (FET) shown as T_1 and T_2 in Figure 1. The drift that occurred during the transition from ambient to vacuum environment was reduced, but not eliminated, by heat sinking the FET pairs to a common metal block. Because of this drift, it was

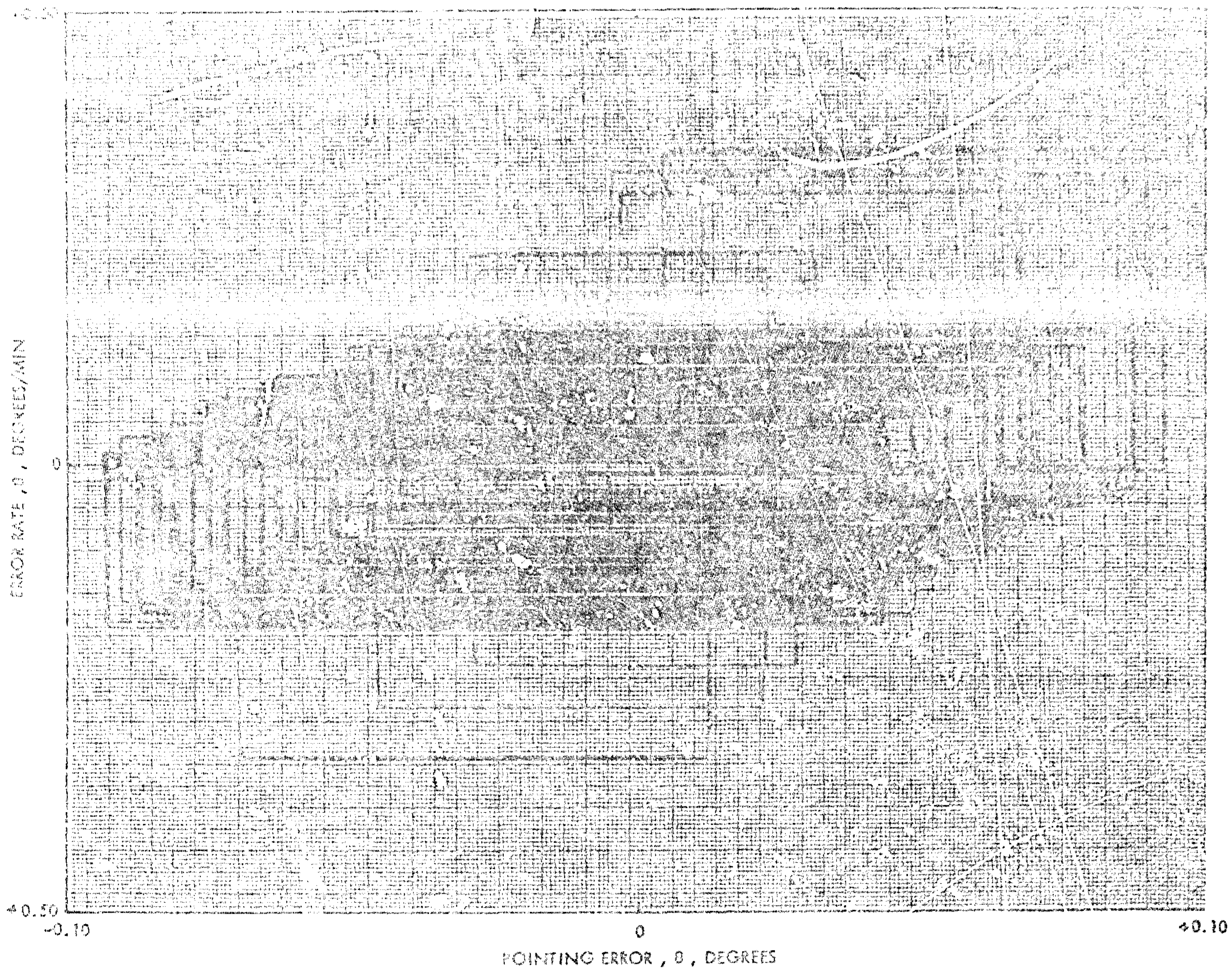


Figure 22. Phase-Plane Plot for Attitude Control

necessary to null the control electronics while under vacuum. Matched pairs of FET's, which will eliminate this drift problem, are now available commercially. The FET's are required to produce a high impedance between the first stage amplifier, A1 in Figure 1, and the lead-lag network. The need for this high impedance results from the high resistance incorporated in the lead-lag network to obtain the required system time constant. Lower resistance values could be used in the lead-lag network, which would eliminate the need for the FET's; however, the capacitors (C_1 and C_2 in Figure 1) would be extremely large.

4.2 THRUSTER TEST RESULTS

The thermal performance of the thrusters was monitored continuously during the test. This was done by recording the voltage and current across the thruster heater element and the output of thermocouples on the thruster core and/or nozzle block. The specific impulse and thrust developed by the thruster were measured at periodic intervals during the test period.

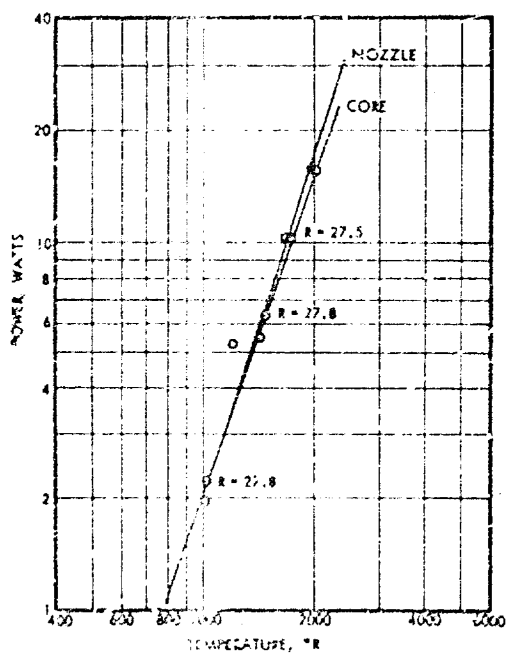


Figure 23. Thruster Thermal Performance, ACSKS -1

4.2.1 First ACSKS Thruster Test Results

A curve of the power required to maintain the thruster core at various temperatures is shown in Figure 23. The heat loss data are representative of those obtained during the initial month of the life test. The thermal performance started to decline with time after this period. The first major change in thermal loss characteristics occurred after a facility power failure. The vacuum chamber became contaminated with pump oil as a result of a relay failure in the test facility interlock system. Build-up of a dark deposit on the nozzle expansion cone section, which was later found to be carbon, became noticeable at this time. The history of the thruster thermal performance is tabulated in Table II. The core average temperature was determined from the resistance of the thruster heater element. The nozzle base temperature was measured with a thermocouple at that location. Periodically, the thruster temperature was allowed to equilibrate at a value near 950°F. In this temperature range, the core average and nozzle base temperatures were nearly the same because radiation heat loss from the nozzle is sufficiently small to have no effect on core temperature distribution. The temperature measured by the heater element resistance was compared to that measured with the thermocouple. The two temperatures agreed to within 5°F throughout the test period. This would indicate that there was no change in the resistance characteristics of the heater element, which was Kanthal N.

Table II. Thruster Thermal Performance

Date	Power Input (watts)	Temperature, °F Core Average	Nozzle Base
8-31-67	14.8	1550	1454
9-30-67	17.2	1600	1485
	14.8	1530*	1420*
10-31-67	17.3	1591	1477
	14.8	1525*	1415*
11-31-67	17.3	1596	1479
	14.8	1528*	1417*

*Corrected to 14.8 watts for comparison with data of 8-31-67.

The specific impulse delivered by the thruster at its operating temperature was monitored periodically, and, on three occasions, the specific impulse delivered as a function of temperature was measured. These data are shown in Figure 24 along with the theoretical specific impulse for the thruster/propellant system. The data was obtained with a nominal ammonia inlet pressure to the thruster of 33 psia. The thrust

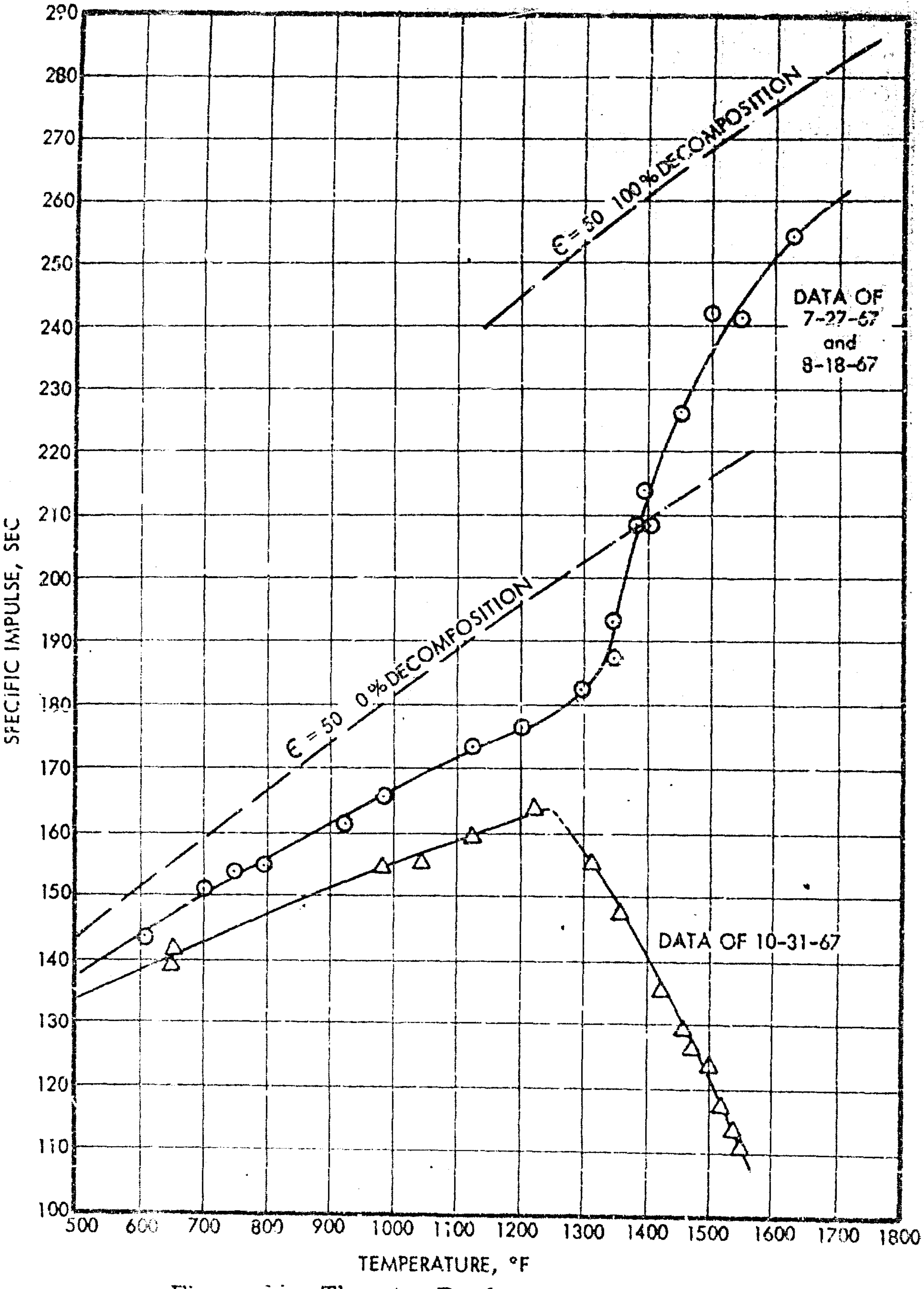


Figure 24. Thruster Performance, ACSKS -1

level was in the range of 0.019 to 0.020 pound over the temperature range. The specific impulse delivered by the thruster was 244 ±3 seconds at 1550°F during most of the test period. These data were consistent with the curve of data for 27 July 1967 and 8 August 1967 in Figure 24. A large reduction in the specific impulse delivered by the thruster occurred during the latter part of October. The specific impulse data as a function of temperature measured at this time are shown in the curve of 31 October 1967 in Figure 24.

The differential expansion of the thruster core with respect to the outer shield as a function of core temperature was measured. This was done by measuring the axial distance between the edge of a nozzle and the edge of the port in the outer shield through which the nozzle protruded. The reference point was established while the thruster core was at 1500°F. The thruster was then allowed to cool and the dimensional change with respect to the reference was measured. The data obtained is shown in Figure 25. No rotation of either the core or outer shield with respect to the thruster bracket was measured. Because of the degraded specific impulse performance, the life test was interrupted and the thruster removed for inspection (see Section 5.1).

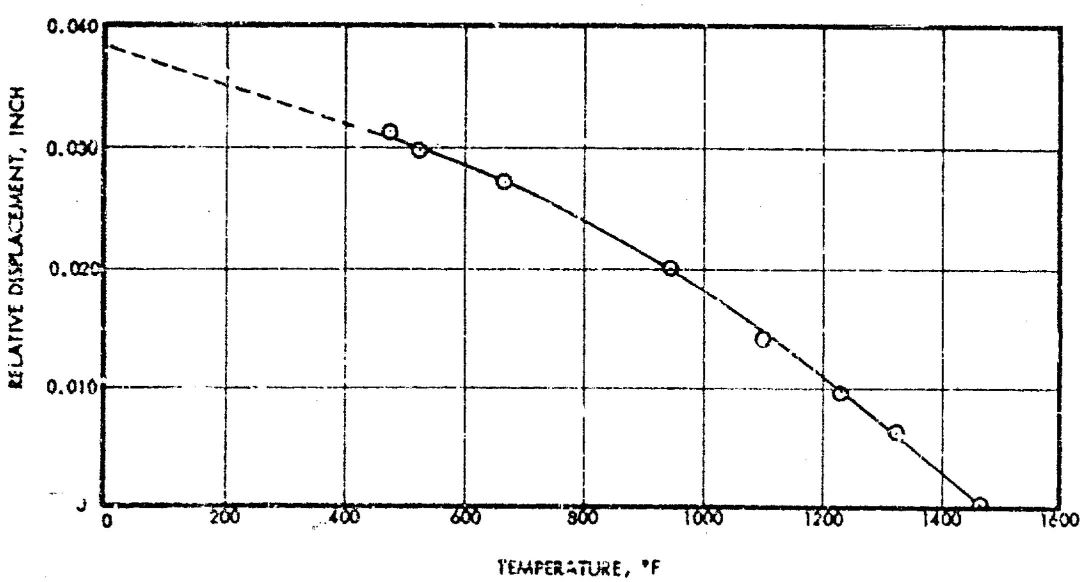


Figure 25. Differential Expansion of Thruster Core and Outer Shield

4.2.2 Second ACSKS Thruster Test Results

This thruster was incorporated in the life test and the test was resumed on 22 March 1968. The initial heat-up of this thructer indicated that a total of 12.0 watts would be required to maintain the thruster at 1500°F. As 1500°F was reached, the power required to maintain this temperature increased and the equilibrium value stabilized at 16.6 watts. On cooling, the thruster assumed different thermal characteristics than on heat-up. These data are shown in Figure 26. The life test was interrupted on 9 April 1968, and the thruster was reinsulated. The test was resumed on 12 April 1968. The thermal loss characteristics of the thruster after reinsulation are shown in Figure 27. A power input of 14.3 watts was required to maintain the thruster at 1500°F.

The specific impulse delivered by this thruster was measured in the nominal operating temperature range. Typical values obtained were:

- 246 ±5 seconds at 1540°F
- 241 ±2 seconds at 1505°F

These data were measured at a delivered thrust level of 0.020 pound. The ammonia pressure at the inlet to the thruster required to maintain this thrust level was 30 psia.

The specific impulse performance of the thruster degraded grossly by the end of July 1968. The life test was interrupted at this time and the thruster removed for inspection (see Section 5.2).

4.2.3 Third ACSKS Thruster Test Results

This thruster, when initially assembled, required 17.1 watts to maintain its core temperature at 1500°F. Because of this high power requirement, the thruster was disassembled and modified. The modification included chemical vapor deposition of nickel on the core and replacement of the Inconel X750 expansion cores of the nozzle with nickel cores. The reassembled thruster required 13.8 watts to maintain a core temperature of 1500°F. After the thruster was integrated into the life test, the power required to maintain a core temperature at 1500°F remained at 13.8 watts. However, the thermal performance began to degrade with time. This degradation coincided with the excessive propellant pulsing that resulted from the sun sensor problem. The thruster thermal

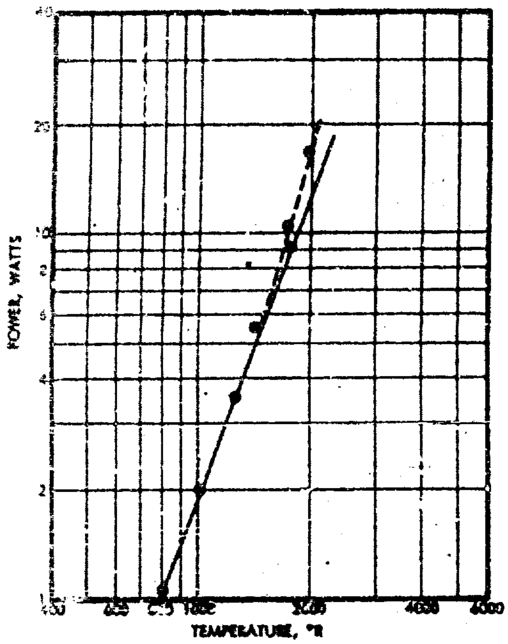


Figure 26. Thruster Thermal Performance, ACSKS -2

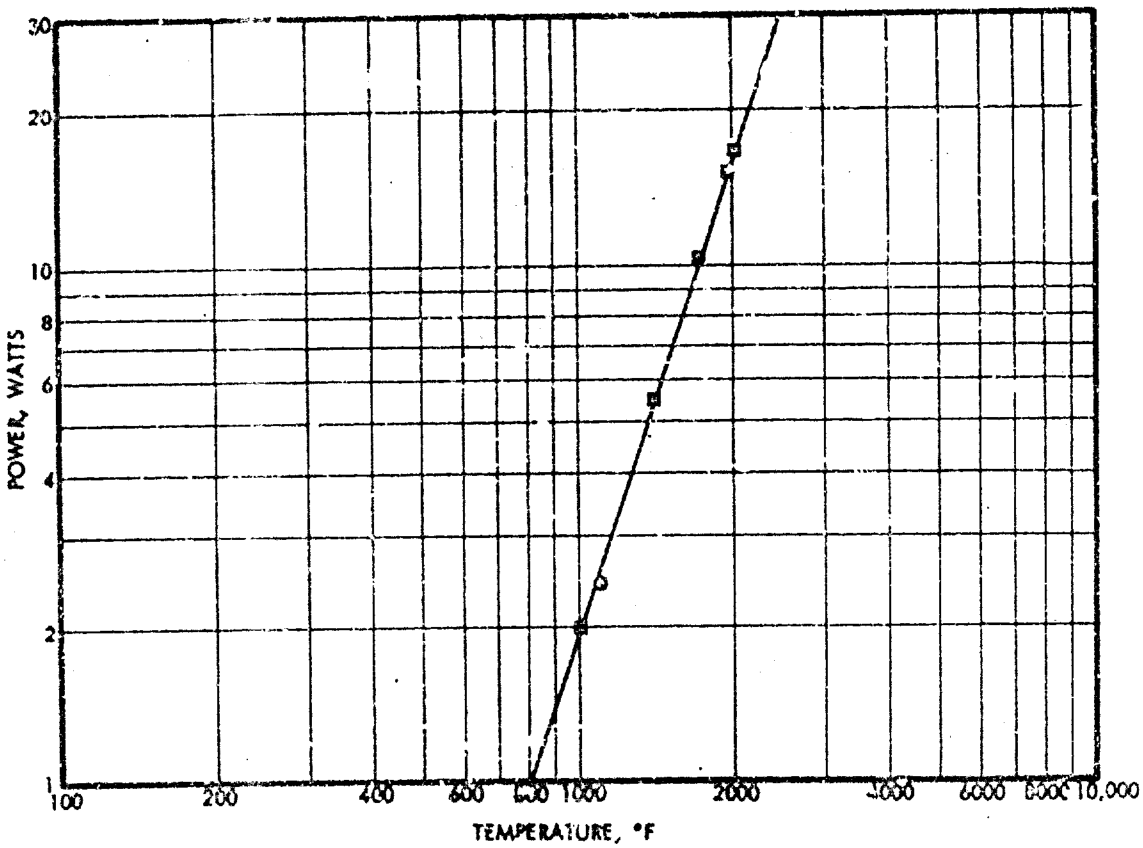


Figure 27. Thruster Thermal Loss, ACSKS -2

performance stabilized at a degraded value after this period. A curve of the thermal performance characteristics is shown in Figure 28. The power required to maintain the thruster core at 1500°F was 16.0 watts. This power level remained unchanged throughout the remainder of the test period.

The specific impulse determined by the thruster was initially 190 seconds at 1500°F. This was the value expected for ammonia with no decomposition. The specific impulse increased to a value of 220 seconds during the first 3 weeks of thruster operation in the life test. These specific impulse values were determined at an operating thrust level of 0.020 pound. An ammonia feed pressure of 35 psia was required to maintain the thrust level at 0.020 pound. During the period that delivered specific impulse was increasing, a series of specific impulse measurements was made as a function of thrust level. These data are shown in Figure 29.

The change in specific impulse as a function of both time in test and thrust level exhibited by this thruster was not noted in the two previous thrusters. The change of specific impulse with time in test might have been due to the removal, with propellant exposure, of a propellant tube surface contaminate. A surface contaminate could reduce the catalytic activity of the flow tube, resulting in a higher average molecular weight of the expelled propellant. A possible source of contamination was the oil used in the drawing operation of the flow tube fabrication. In the event that oil entered the flow tube during the drawing operation, it would have left a carbonaceous deposit which could not be removed by normal cleaning procedures. The purging action of the propellant, while the thruster was at operating temperatures, might have been responsible for removal of a portion of the contamination, which resulted in the improved specific impulse performance.

In an attempt to achieve maximum propellant tube surface catalytic activity, air was pulsed through the tubes. A total of 14.5 cubic inches of air at S.T.P. was pulsed through the two flow tubes used in normal mode control. The thruster core was maintained at 950°F and the propellant was pulsed at a 5 percent duty cycle with a 1-second ON time. A check of the thruster delivered specific impulse at 1500°F indicated that there was essentially no performance improvement over the pretreatment

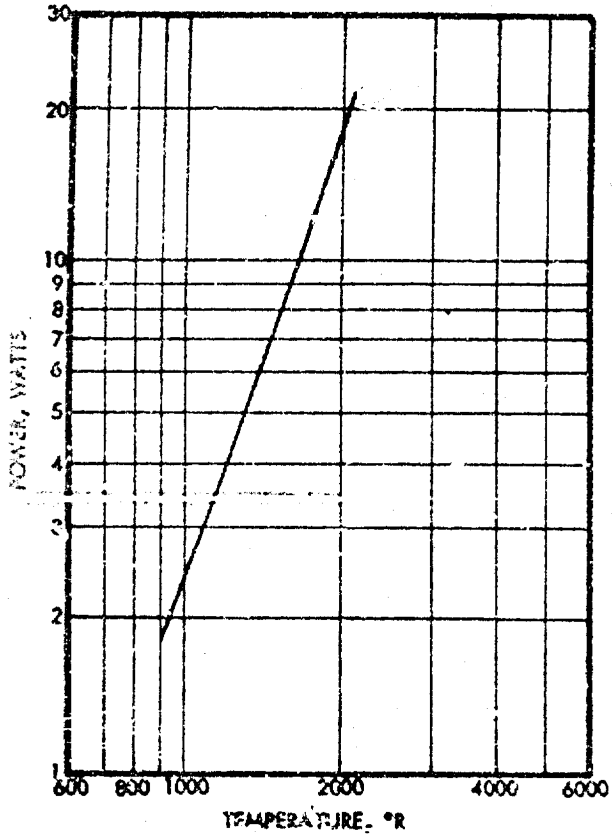


Figure 28. Thruster Thermal Performance, ACSKS -3

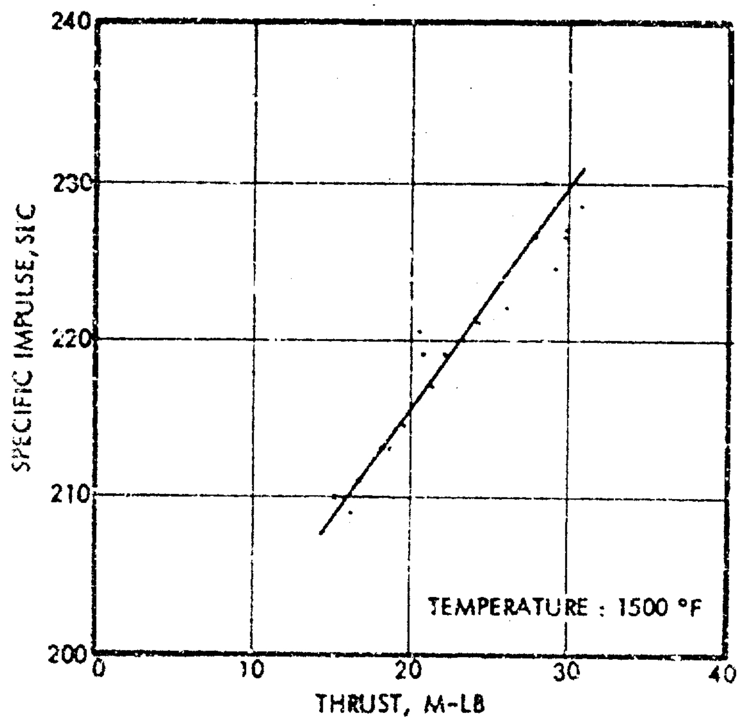


Figure 29. Thruster Performance, ASCKS -3

value. The air oxidation treatment was repeated, but with the thruster core maintained at 1250°F. A curve of the specific impulse as a function of thrust level at 1500°F is shown in Figure 30. The specific impulse was still dependent on the thrust level, as it had been before the air treatment; however, at the nominal 0.020 pound level, it had increased to 226 seconds. The air oxidation of the flow tubes was again repeated with 7.0 cubic inches of air at S.T.P. and with the thruster core maintained at 1500°F. The curve of specific impulse as a function of thrust is shown in Figure 31. There was no improvement in the specific impulse delivered at the 0.020 pound thrust level; however, the specific impulse increased from the 231-second pre-treatment value to 241 seconds at a 0.030 pound thrust level. The data indicated that the specific impulse was approaching a limiting value as the thrust was increased. Because of the pressure limitation of the feed system pressure monitoring transducer, it was not possible to obtain data at higher thrust levels.

There was no, or at most only a small, variation of specific impulse with thrust level noted on the other thrusters tested. The previous thrusters appeared to produce nearly complete ammonia decomposition over the thrust levels, and consequently, the propellant flow rates tested. The specific impulse variation of this third thruster with thrust level was sufficiently large to be almost totally attributable to differences in fraction of ammonia decomposed. Another factor which affects specific impulse is the change in nozzle efficiency with the Reynolds number in the nozzle throat. With all other parameters constant, the nozzle efficiency is a function of propellant mass flow rate and, therefore, thrust level. The nozzle efficiency variations over the thrust level ranges tested would be small. The difference in operating characteristics of this thruster, compared with those of the previous thrusters, has been attributed to the physical characteristics of the flow tubes. The flow tubes of this thruster had thicker walls than the previous ones. The liner of the composite tube used on this thruster was equivalent to the previous thruster flow tubes. In addition to this liner, the composite tube had an outer sheath that was almost of equivalent thickness. This heavier walled tube retained its circular cross-section when it was coiled on the thruster core, whereas there was some ovalness in the cross section of the tubes of the previous thrusters after they were coiled on the core. This oval cross-section

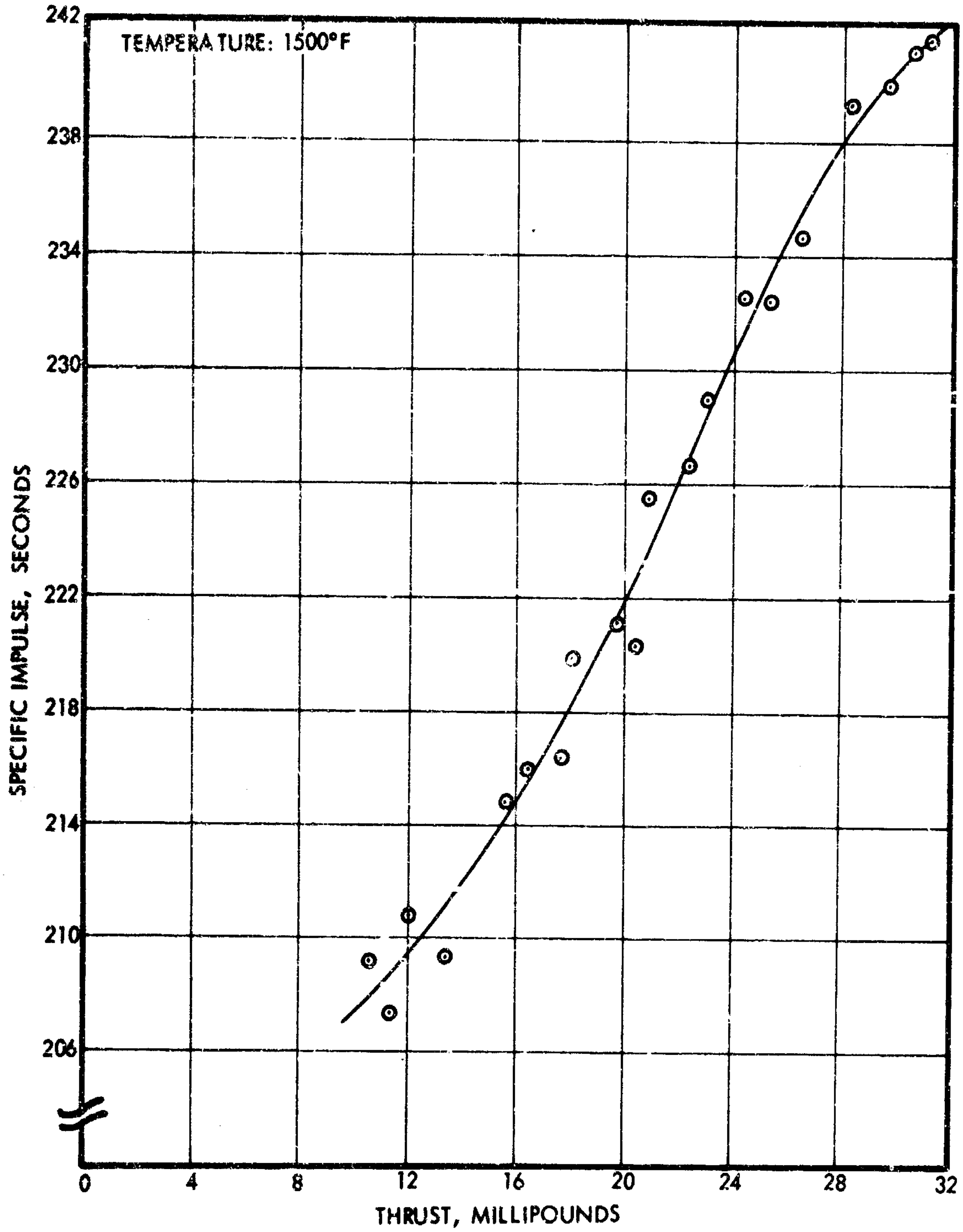


Figure 30. Thruster Performance, Second Oxidation, ACSKS -3

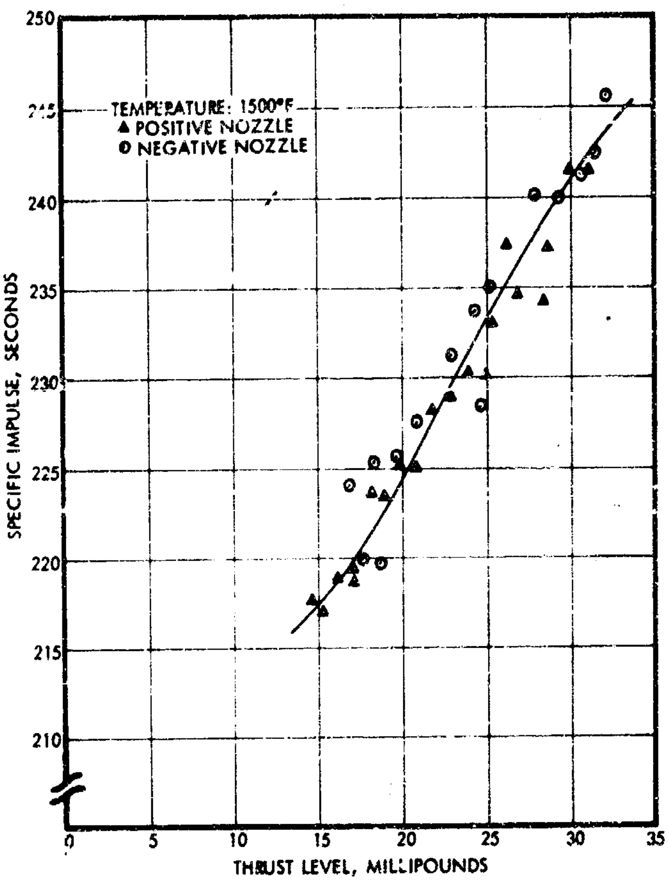


Figure 31. Thruster Performance, Third Oxidation, ACSKS -3

would result in increased flow stream turbulence compared to that of a circular cross-section at the same flow rate and temperature. The increased turbulence would result in a higher ammonia decomposition rate per unit length of tube. The flow condition in the thruster propellant tubes is designed to be in the transitional region between turbulent and laminar flow. In this flow regime, turbulence in the flow stream is suppressed in a coiled tube with a circular cross-section. A small change in flow rate, however, does have a large effect on the degree of turbulence in the flow stream. The effect would cause the ammonia fraction decomposed to increase with increasing flow rate. Thus, the specific impulse delivered by the thruster would increase as thrust level increased until complete decomposition occurred.

4.3 AMMONIA FEED SYSTEM TEST RESULTS

The ammonia feed system performed within design limits throughout the entire integrated system life test. The feed system storage tank was initially charged with 12.25 pounds of ammonia, approximately one-half of its total capacity. The system delivery pressure was adjusted to 33 psia, so that the first ACSKS thruster would deliver 0.020 pound of thrust. The pressure control limits at the nominal operating temperature of 72°F were ±0.4 psi with liquid leaving the tank and ±0.08 psi with vapor exhaust. At a storage tank temperature of 100°F, which resulted in a tank pressure of 214 psia, the pressure control limits with liquid leaving the tank increased to ±0.5 psi, but remained essentially unchanged with vapor.

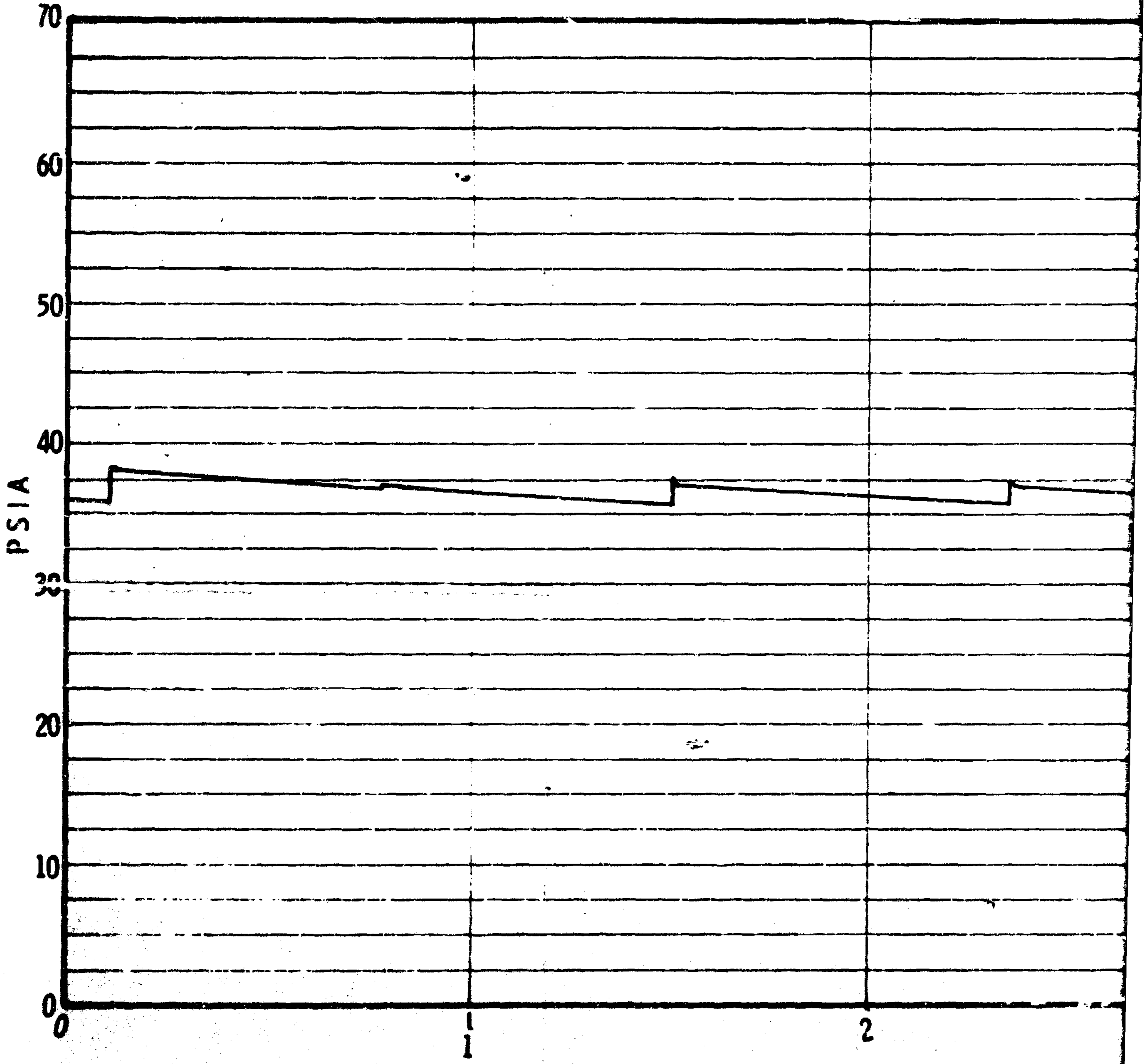
Shortly after initiation of the integrated system test, random increases in the pressure control limits of the feed system developed. On several occasions, the control limits increased by a factor of four over that of the original. This anomaly in pressure control was traced to radiative noise pickup in the transducer/switch circuit. The magnitude of this noise level in the circuit was sufficient to cause opening of the propellant source control valve at pressure levels above the upper control limit.

The source of the noise was test equipment that was operated in the same building as the ACSKS test. Because of the integrated test wiring layout, it was not convenient to effectively shield the pressure control circuit from the noise; therefore, a "tee" filter was incorporated in the transducer output line. This filter stabilized the pressure control band; however, it introduced a delay in the output transient signal from the control transducer. This resulted in an increase in the control pressure band width with liquid exhaust from the propellant storage tank. At the nominal ambient operating tank pressure, the flow rate through the capillary tubes with liquid exhaust from the tank was approximately 50 percent higher than with vapor exhaust. The tee filter was matched to the rate of change of transducer output resulting from the pressure rise in the plenum when vapor phase ammonia was leaving the storage tank. When liquid was exhausted from the tank, there was a mismatch between the transducer signal rate of change and the time constant of the filter. This caused a delay in the transducer signal to the switch. The pressure control limit with the filter was ±0.8 psi with liquid phase ammonia entering.

The nominal control pressure level delivered by the feed system was reduced from 33 psia to 30 psia during the test period of the second ACSKS thruster. This was required to maintain the delivered thrust of 0.020 pound. The storage tank was also recharged with ammonia to a contained weight of 12 pounds. The pressure control limits during this test period were ±0.8 psi with liquid phase entering the capillary tubes and ±0.8 psi with vapor.

The storage tank was again topped with ammonia to bring its contained weight to 12 pounds before testing the third ACSKS thruster. The nominal control pressure level was adjusted to 35 psia. This was the pressure required by the third ACSKS thruster to deliver 0.020 pound of thrust. The tee filter in the electronic control switch sensing circuit was modified to reduce the system response delay when liquid was exhausted from the tank. The pressure control limits during the final test period were ±0.45 psi with liquid flow and ±0.08 psi with vapor flow. A 24-hour record of delivered pressure during thruster normal mode operation and with liquid exhaust from the storage tank is shown in Figure 32.

After termination of the life test, the feed system was operated at a flow rate corresponding to that required for the mission acquisition maneuvers. The storage tank pressure was 95 psia at the start of the test and the flow rate adjusted to 4×10^{-4} lb/sec. The storage tank contained 6.0 pounds of propellant at the initiation of this test and the tank was positioned for extraction of liquid phase ammonia. The system maintained this flow rate for a period of 420 seconds before there was evidence of liquid phase ammonia discharging from the capillary tubes. Normal acquisition would occur with the tank filled to maximum capacity (22 pounds) and the total flow rate of 4×10^{-4} lb/sec would be supplied by two independent feed systems for a period of only 300 seconds. The results of this test indicated that the system has the capability of satisfying the most stringent mission requirement after 2 years of service. A total of approximately 20 pounds of ammonia had been delivered by the system during this period.



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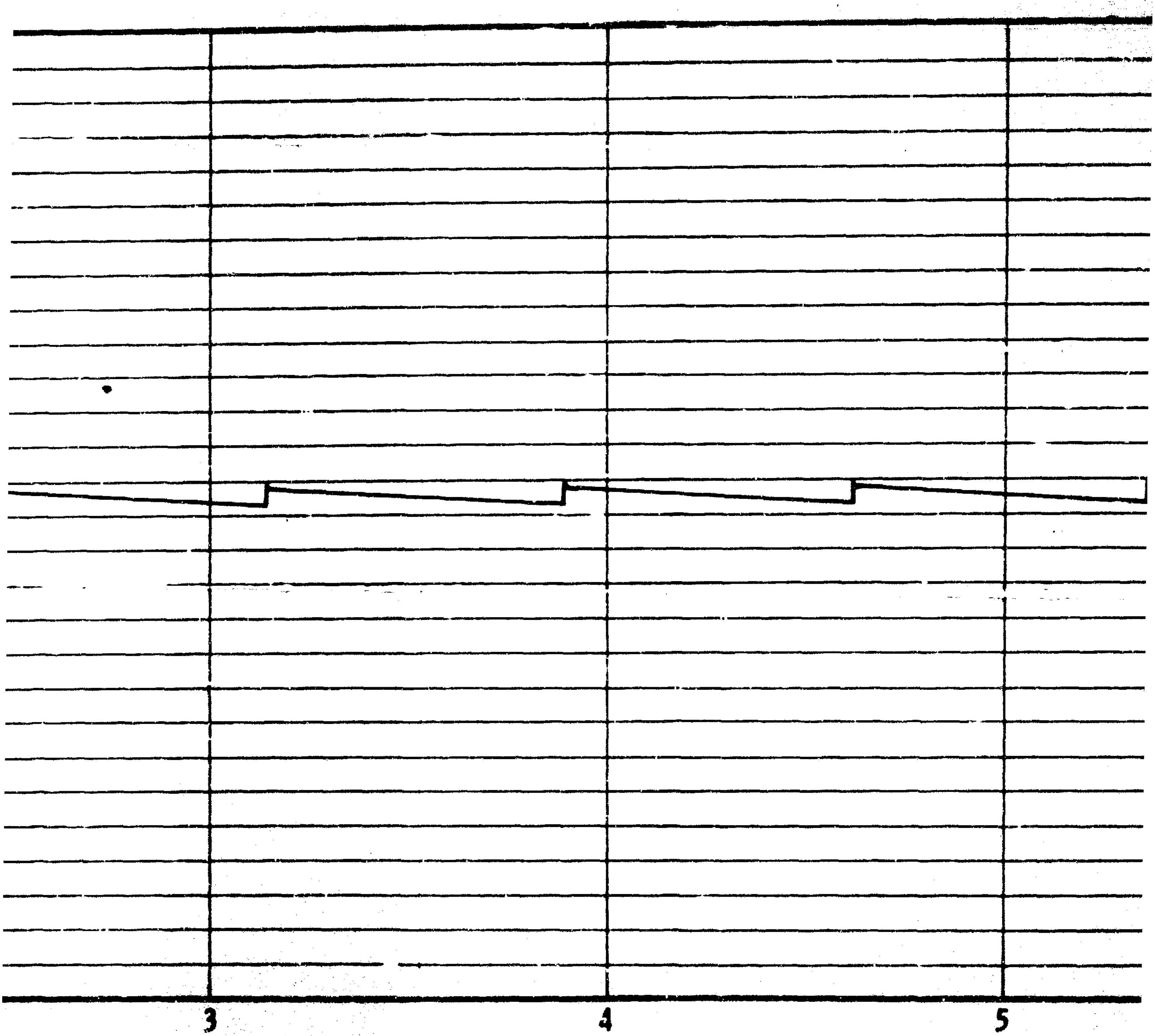

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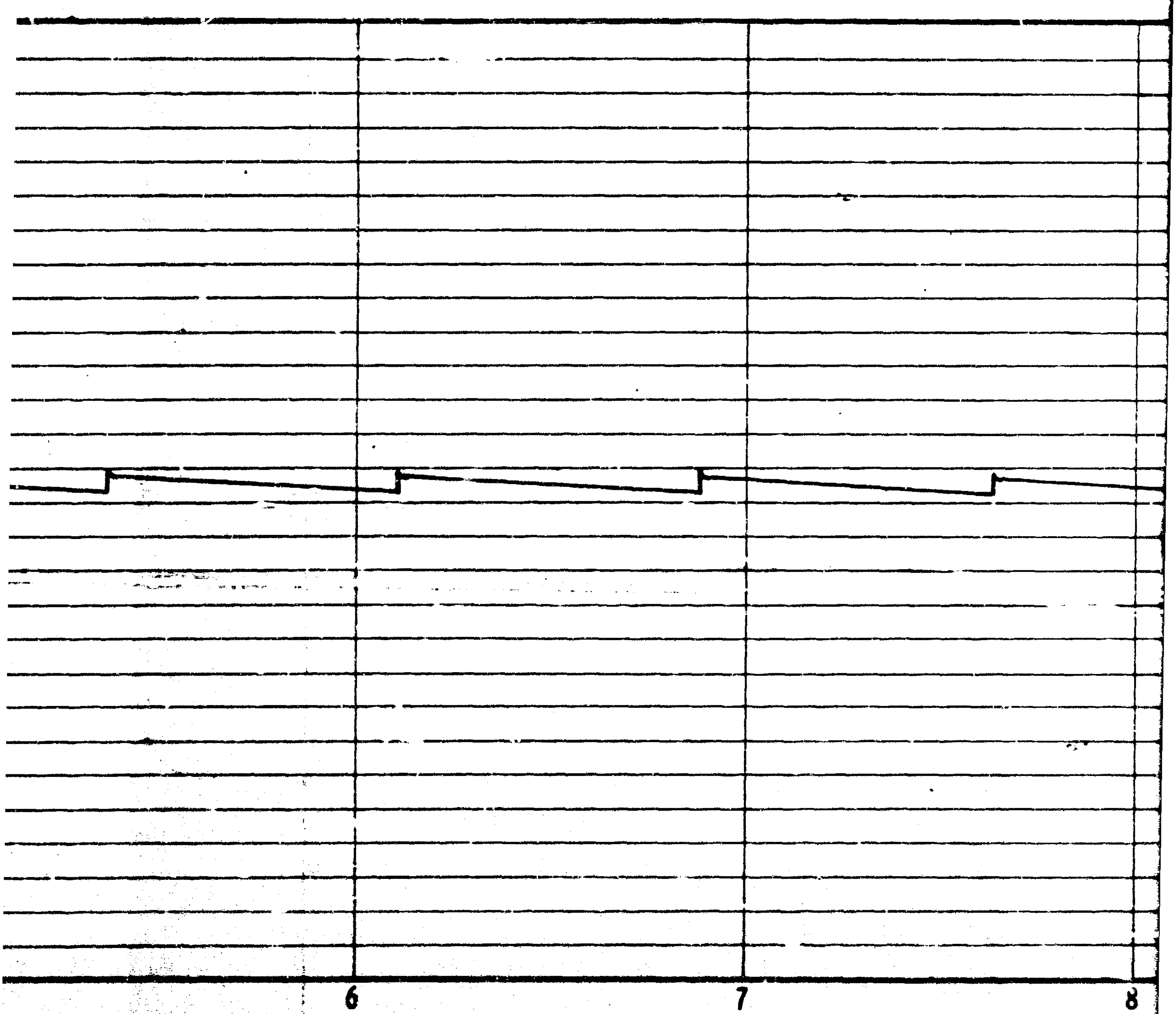

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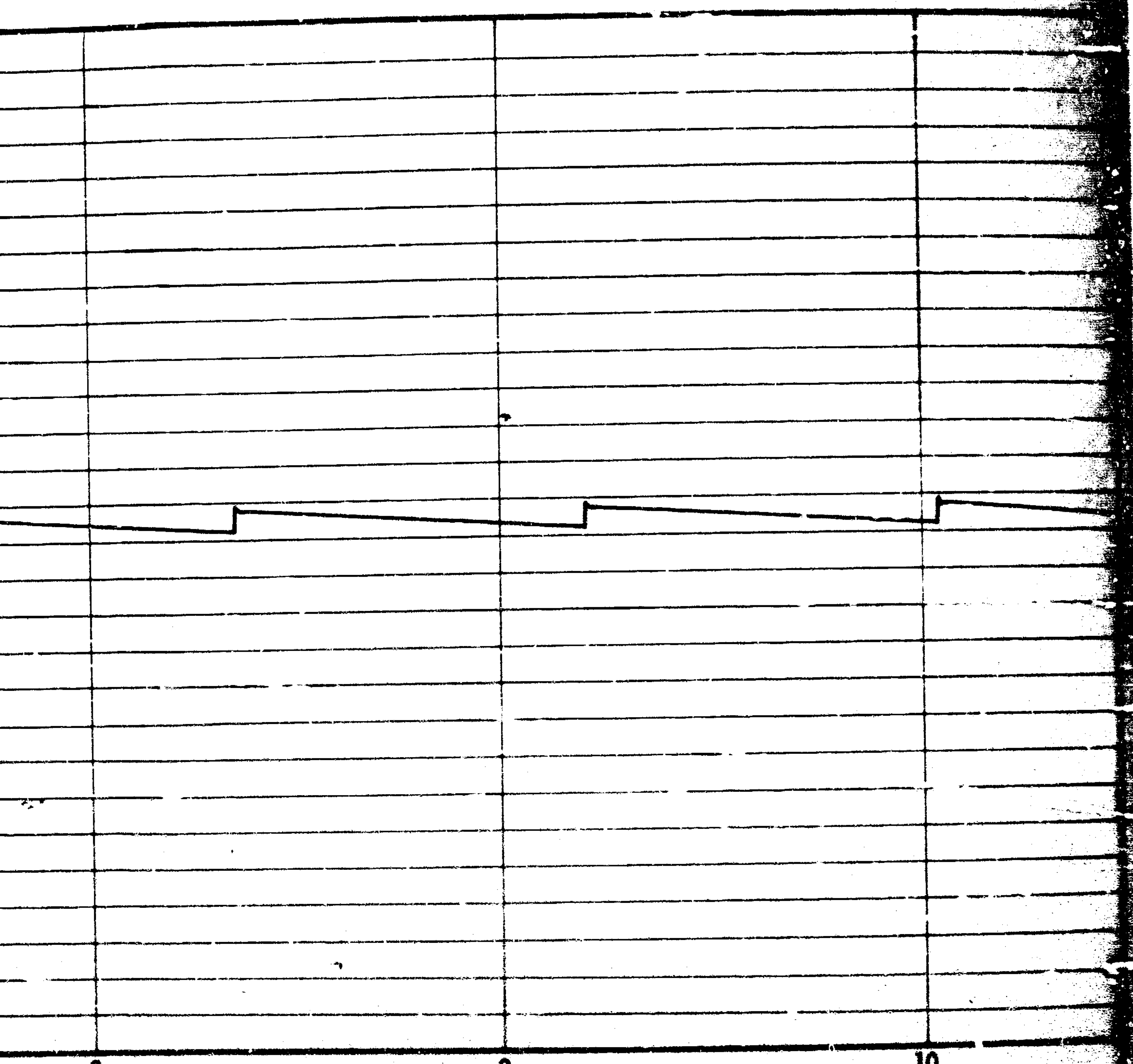

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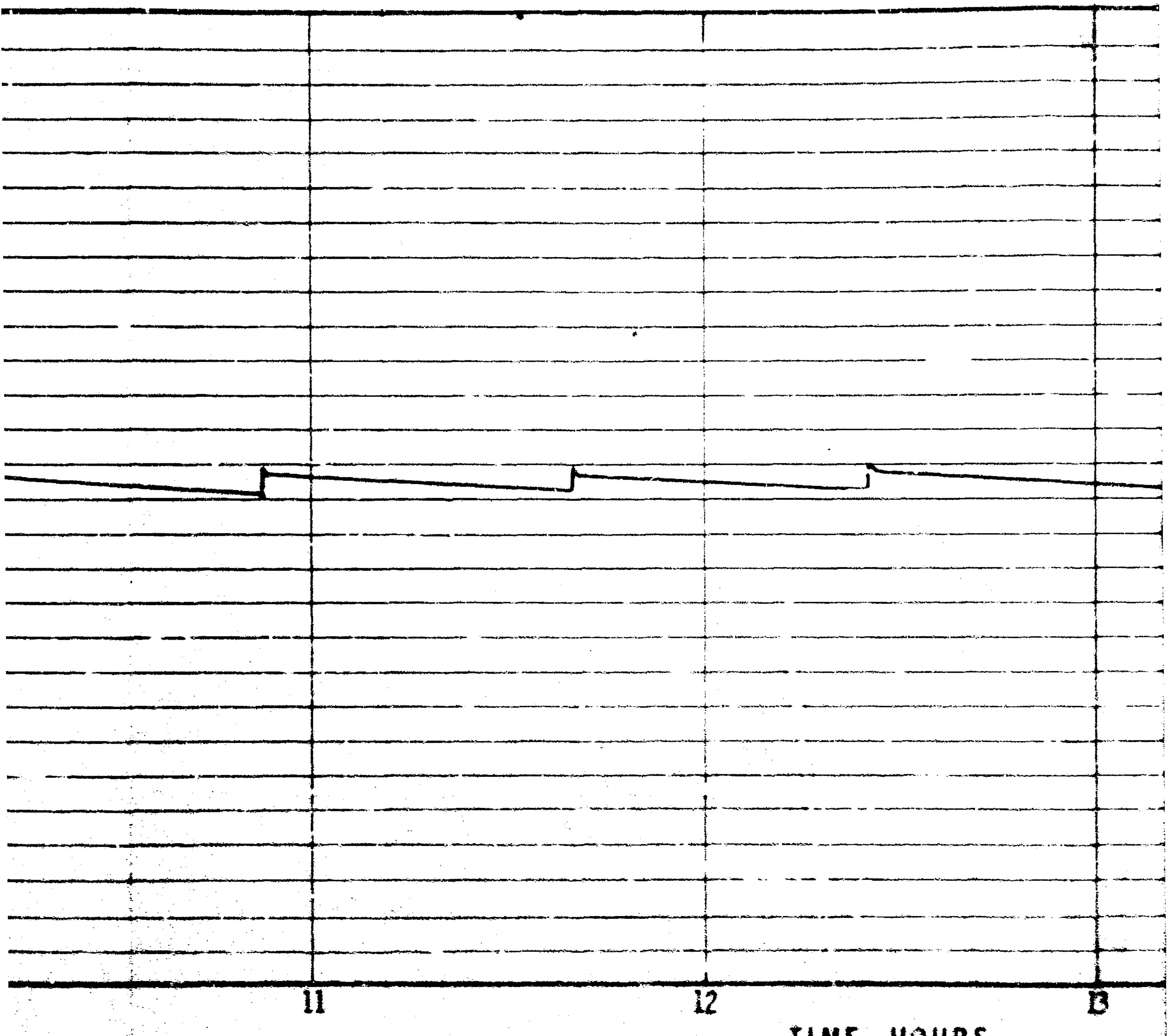

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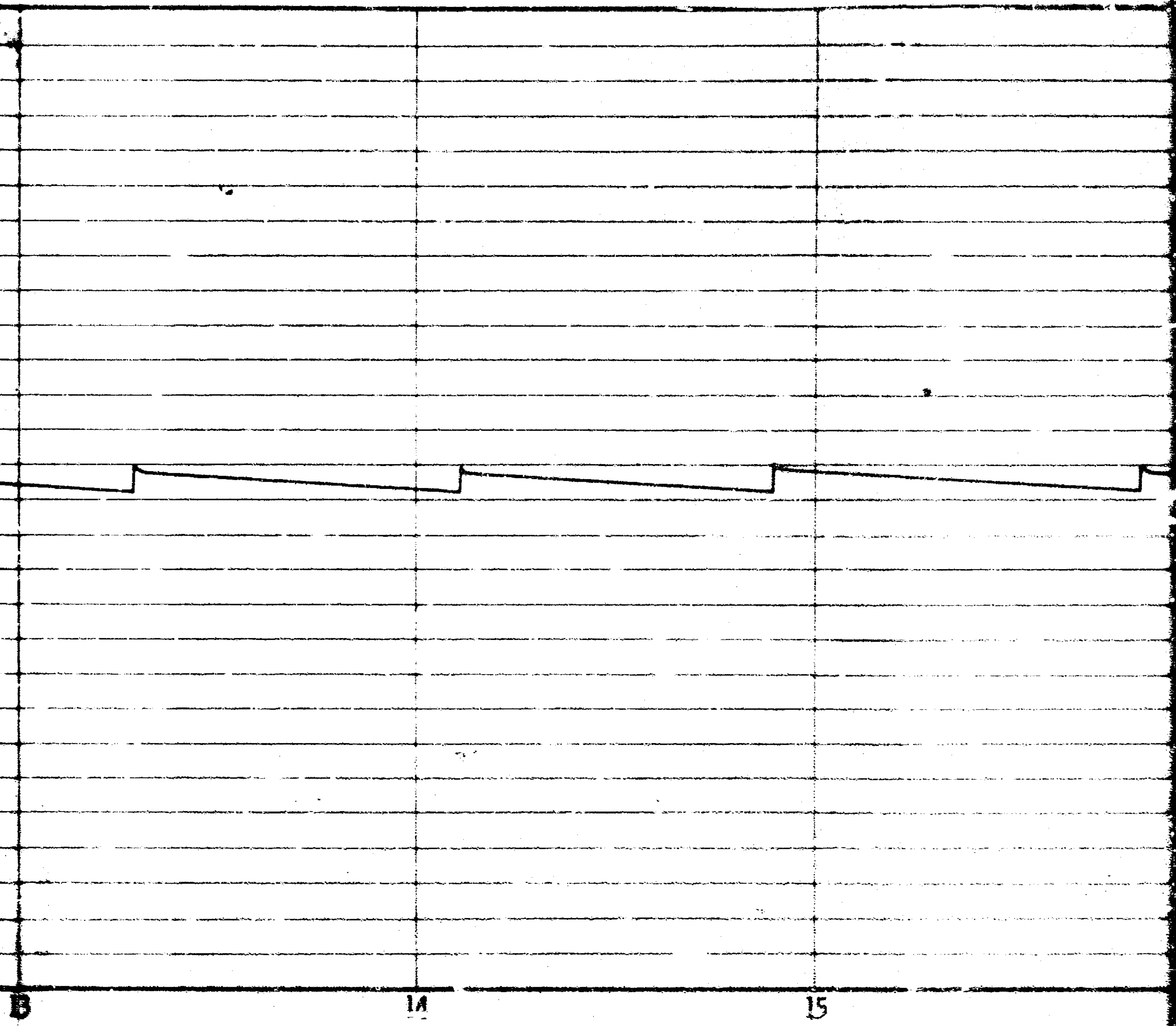

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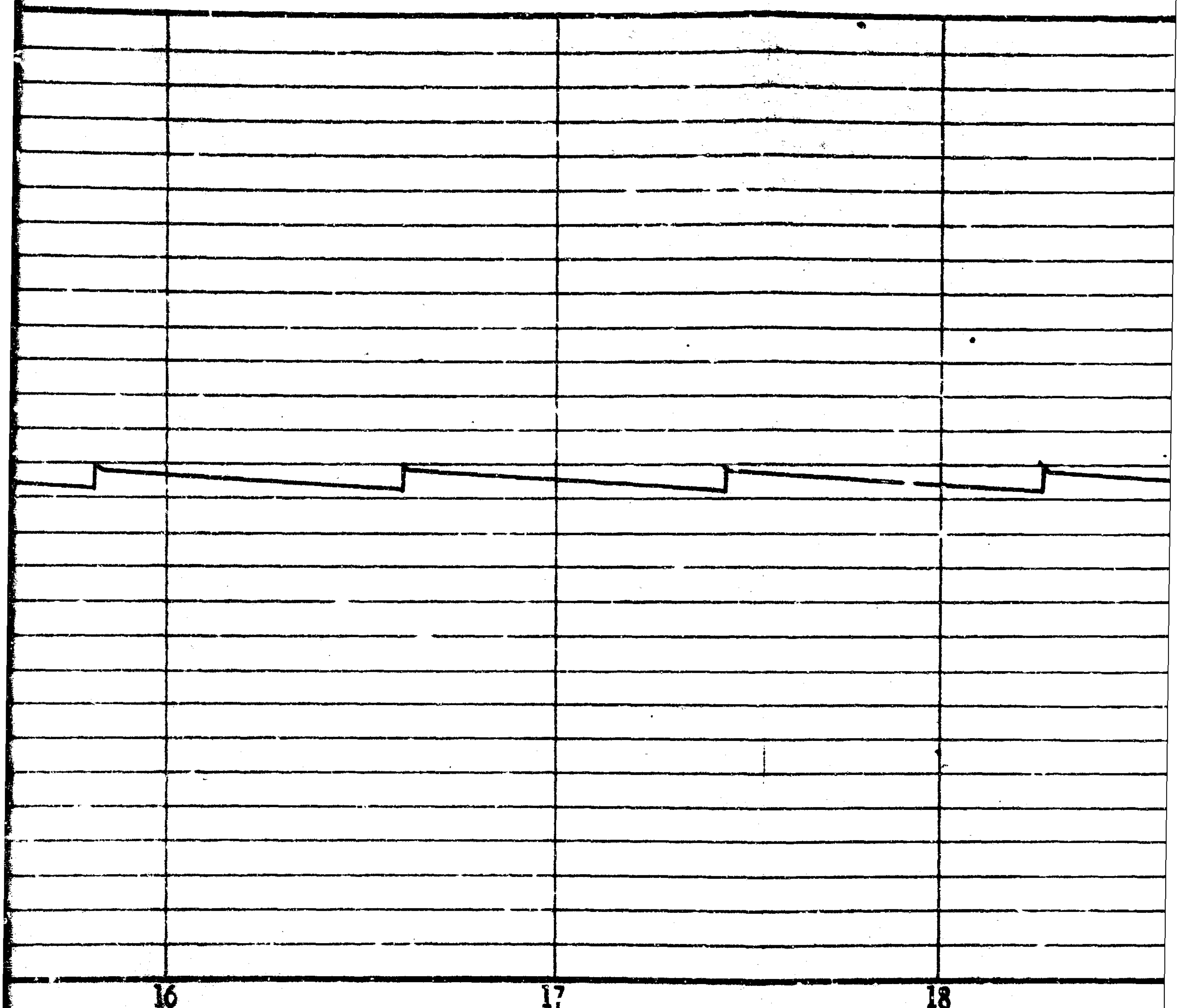

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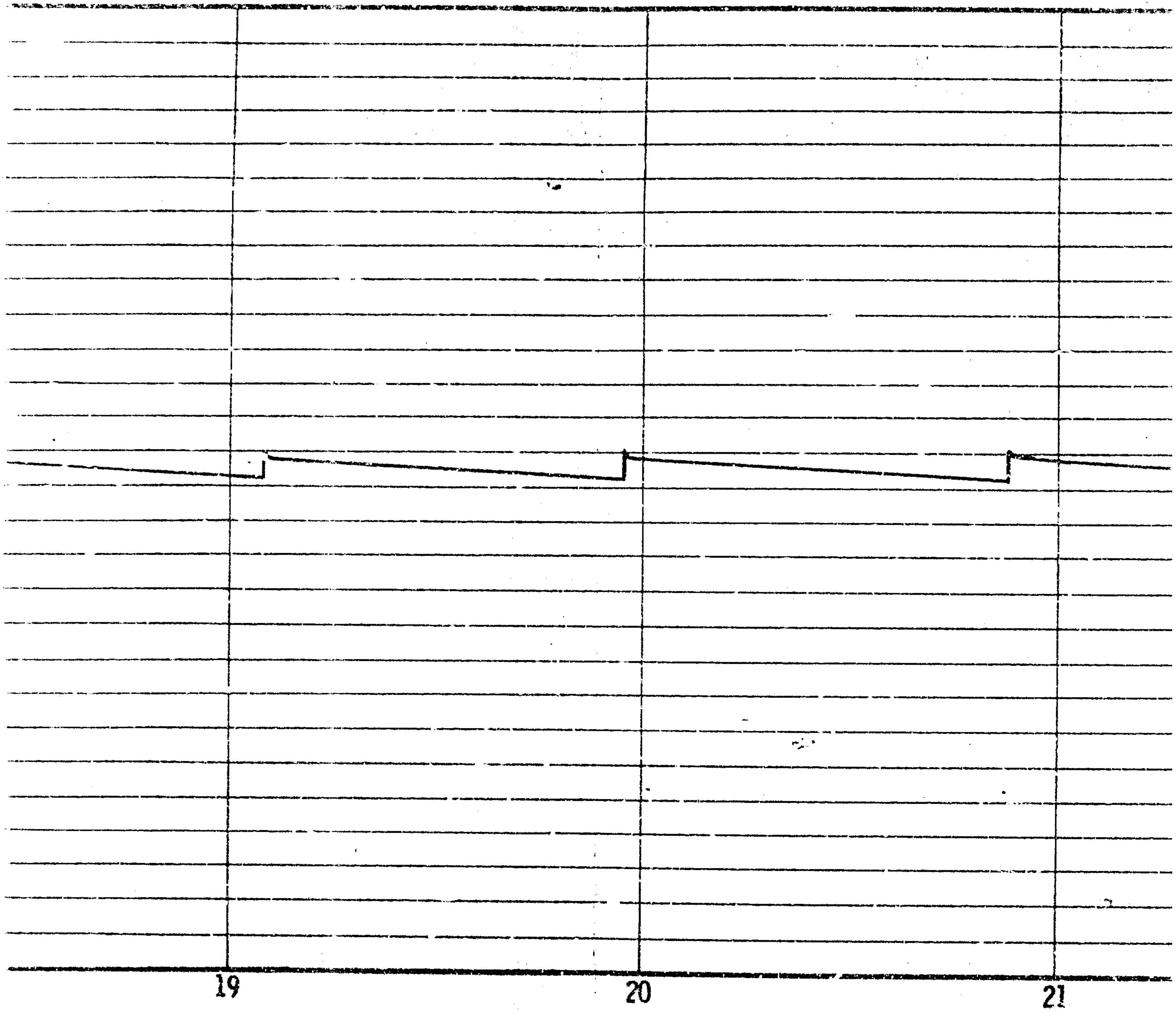

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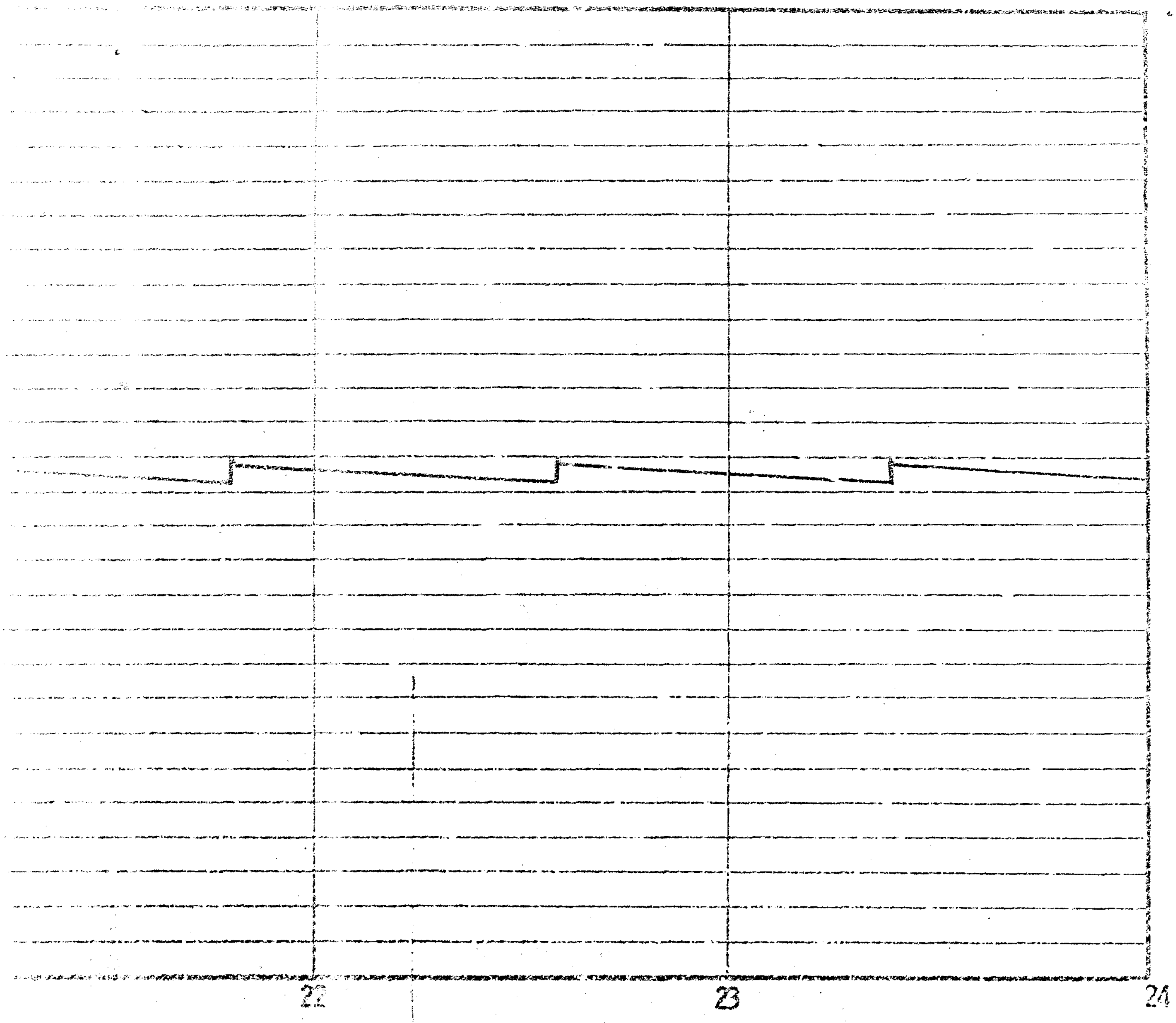

Figure 32. Feed System Delivered Pressure, 24 Hours

5. THRUSTER POST-TEST ANALYSES

Because of the program schedule, only short-term material test results were available for incorporation into the design of the first demonstration thruster used in the life test. The major output of the short-term tests was the data used to select a braze material with a sufficiently low sublimation rate for the thruster operating life. In order to obtain long-term compatibility data, a materials and heater element evaluation program was initiated along with the hardware development program. The object of the materials evaluation was to determine the interactions between the various structural materials used in the thruster. These evaluation tests were performed with the various materials in contact at the typical thruster operating temperature range. Some tests were performed at higher than nominal operating temperature to obtain results under accelerated conditions. The most meaningful tests for these evaluations were performed as an integral part of the heater element evaluation tests. In these dual evaluation tests, a heater element and flow tube sample were brazed to a base core in a manner similar to that of the thruster core. The materials of construction of the items on the core samples were typical of those that would be used in an operational thruster. These heater element/core assemblies were insulated with either Dynaquartz or super insulation similar to that used on the thrusters. The samples were heated in a vacuum chamber with the heater element used as the heat source.

5.1 FIRST ACSKS THRUSTER

The materials of construction of the first ACSKS thruster, i.e., the heater element wire and sheath, the flow tubes, the core base, and the braze material, were selected on the basis of the short-term materials evaluation tests and prototype thruster tests. However, the flow tubes of this thruster failed after being in test for a period of 154 days. A photograph of the thruster core after removal from the life test is shown in Figure 33. A photograph of a similar thruster core in the as-brazed condition is shown in the figure for comparison. Aside from the darkening of the core surface and nozzle expansion cones, the first visible signs of the flow tube failure were cracks in the flow tubes in a region upstream of the core. A photograph of a failed flow tube is shown in Figure 34. Although the tube was cracked, the actual complete separation occurred during removal of the thruster insulation. This fracture was located approximately 1/4 inch upstream of the core. Dimensional orientation can be obtained from Figure 4. The thruster core was sectioned for metallographic and chemical analysis. A photograph of the sectioned core is shown in Figure 35 and a close-up of the flow tubes near the entrance end is shown in Figure 36. The tubes are identified as ΔV, positive, negative, and unused, denoting the nozzle to which they supplied propellant. The ammonia time exposure decreased in the order listed. The unused tube was exposed only during initial unit testing. The damage sustained by the flow tubes, as can be seen in Figure 35, was essentially proportional to the ammonia exposure time. Close-up photographs of a flow tube as it progresses to the nozzle are shown in Figures 37a, 37b, and 37c. The extent of the damage to the flow tube decreases as it approaches the nozzle. The damage to the flow tubes was minimal, and about the same for all the tubes used in the test, at the entrances to the respective nozzles.

Various regions of the flow tubes were analyzed for chemical composition by an electron beam microprobe. The objective of this analysis was to determine the nitrogen content in the propellant flow tube wall. The results indicated that the flow tube wall in the vicinity of the fractured portion contained 7 percent nitrogen by weight. A compound such as Fe_3N contains 7.5 percent nitrogen by weight. This section of the flow tube, upstream of core, was exposed to an estimated temperature of between $900^{\circ}F$ and $1200^{\circ}F$. No nitrogen, or only a negligible quantity, was found in the flow tube wall located on the core section of the thruster. The core section of the thruster was maintained at a temperature above $1500^{\circ}F$ during operation. Formation of stable nitrides in stainless steel, the flow tube material, occurs in the temperature range of $900^{\circ}F$ to $1100^{\circ}F$, Reference 2. Below this temperature range they do not form in the presence of nitrogen or nitrogen containing compounds, and above the temperature range, they are unstable.

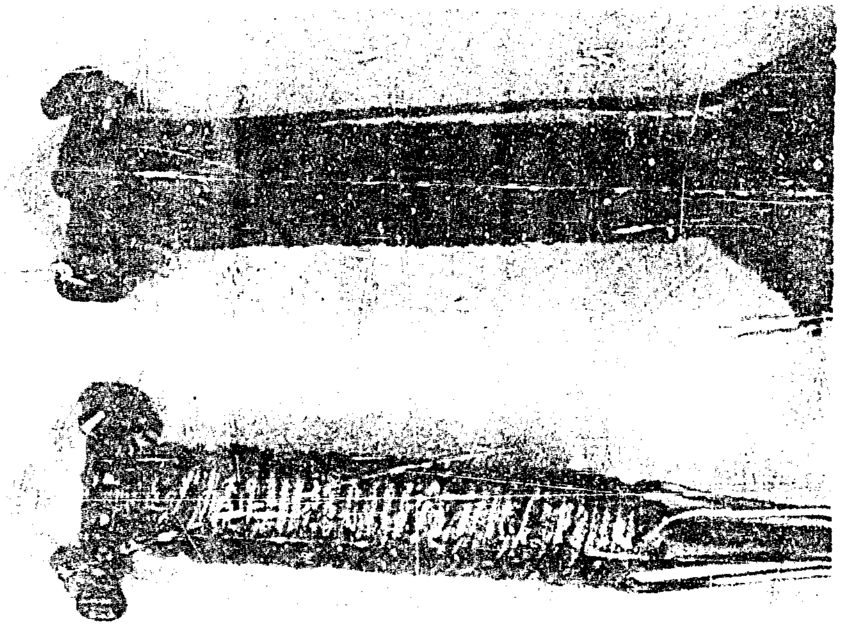

Figure 33. Post-Operational ACSKS -1 Thruster Core

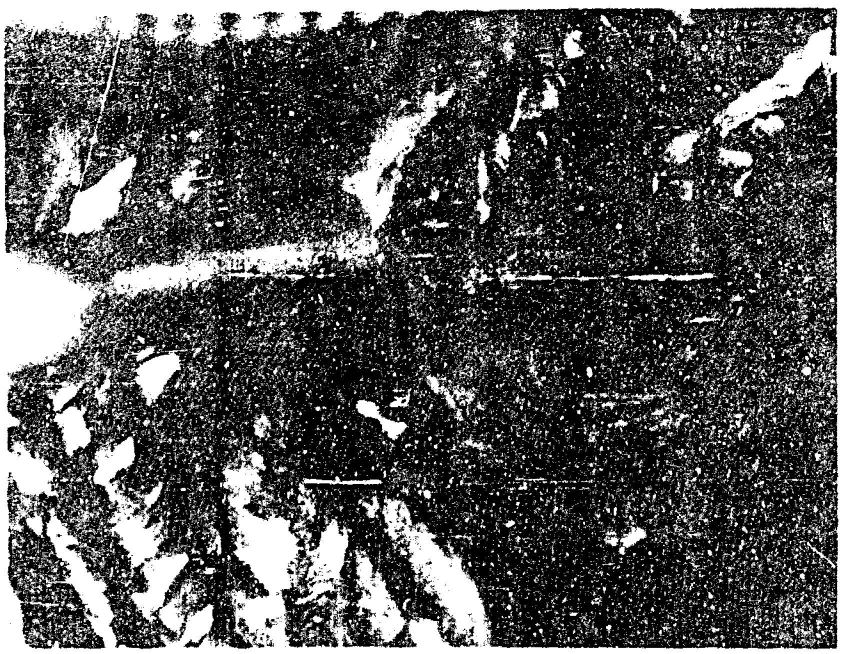

Figure 34. Propellant Flow Tube

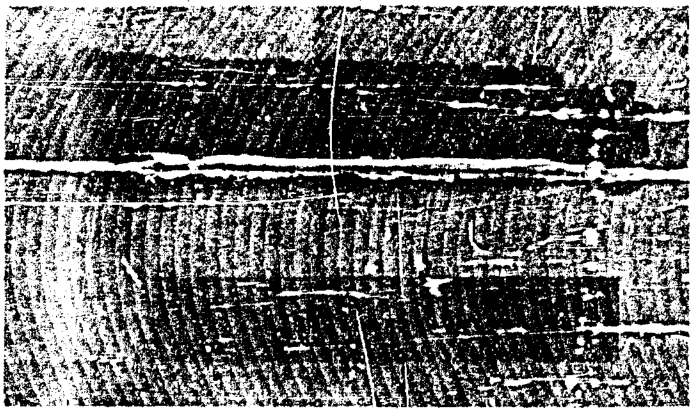

Figure 35. Sectioned Thruster Core, ACSKS -1

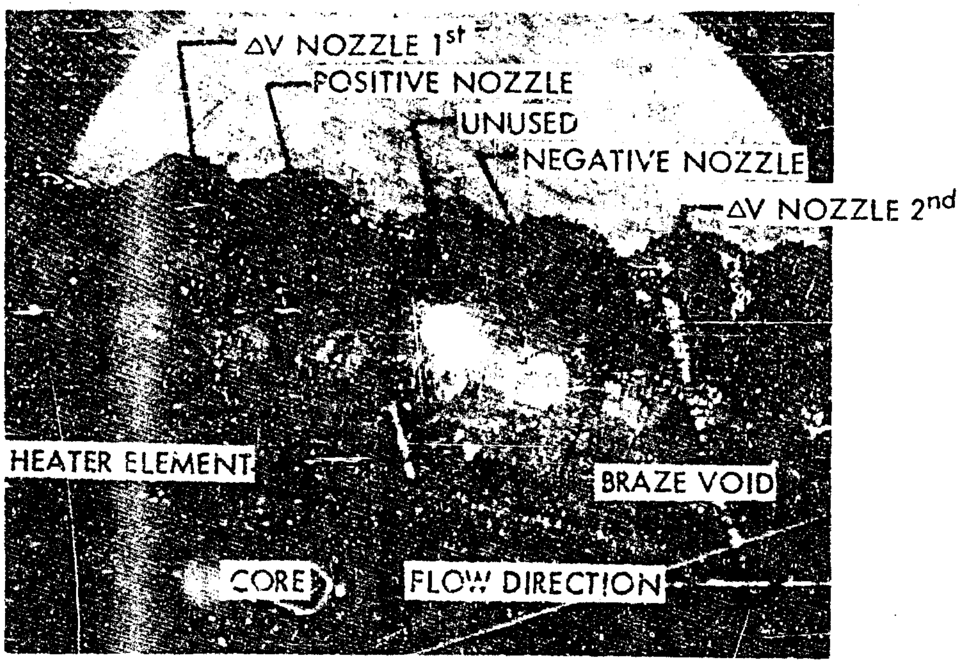

Figure 36. Thruster Core Section, ACSKS -1

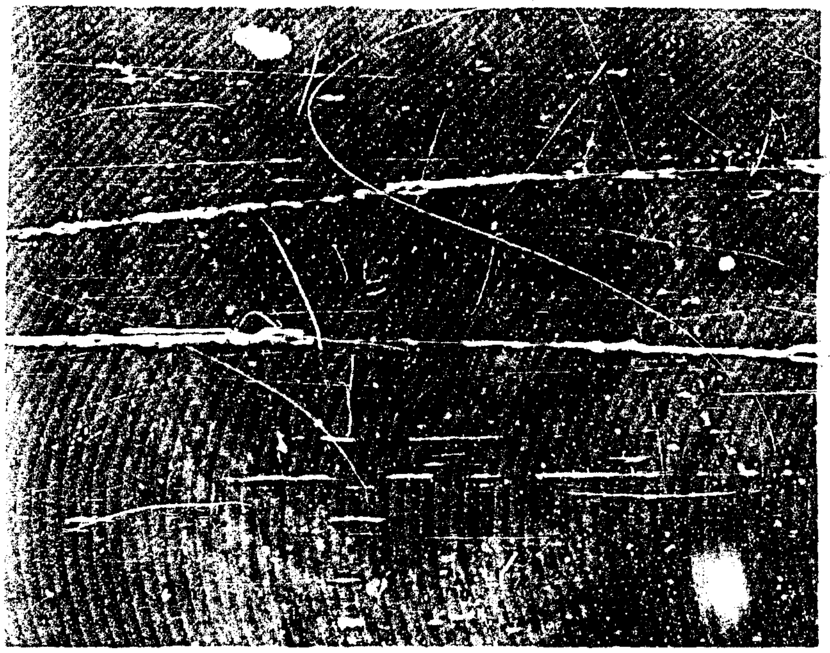

Figure 37a. Flow Tube Cross Section—Entrance End

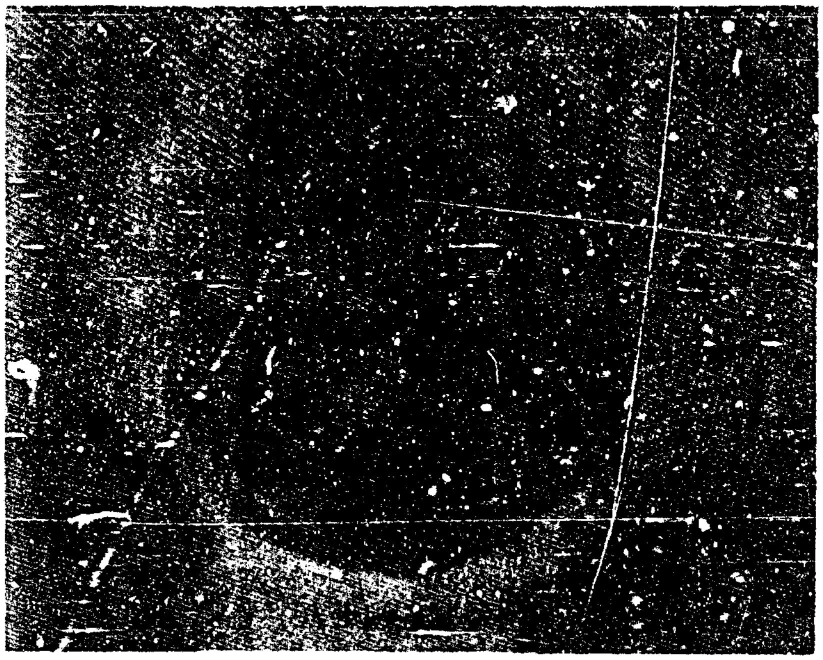

Figure 37b. Flow Tube Cross Section—One Third of Coil Length

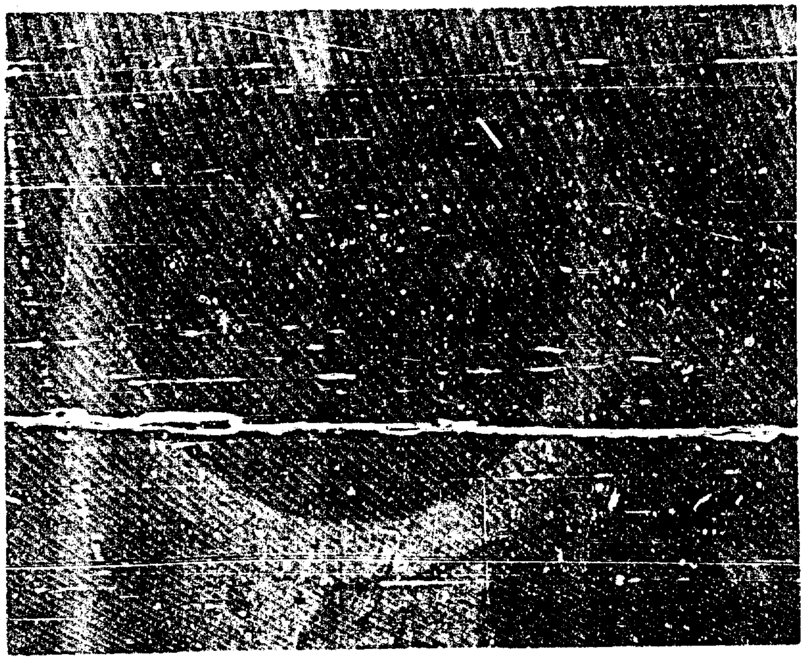

Figure 37c. Flow Tube Cross Section — Two Thirds of Coil Length

Results of the catalytic activity studies with stainless steel flow tubes during the development phase of the program indicated that the decomposition of ammonia under dynamic conditions was predominately a kinetic controlled process at surface temperatures below 1250°F and a diffusion controlled process above this temperature. It has been postulated that a reaction in a flowing system can become diffusion controlled when one of the species forms an unstable complex with the catalytic surface, and that its lifetime is short compared to the system diffusion time. The experimental data appeared to verify this premise by the fact that no nitrogen was found in the tube material on the thruster core. In addition, the damage to the flow tubes on the thruster core appeared to be in direct relationship to the ammonia concentration to which they were exposed. This was concluded from the fact that the damage to the flow tube decreased as it approached the nozzle, coinciding with the decrease in ammonia concentration due to its decomposition along the flow tube. The flow tube wall was at constant temperature along the core even during propellant pulses. Thus. temperature effects on flow damage did not exist. The more catastrophic failure in the flow tube occurred in the region where stable nitride formed. However, the damage sustained by the flow tubes in the regions where nitrogen was not found by the electron beam probe analysis was sufficient to cause a failure eventually. The flow tubes were brittle as a result of this type of ammonia attack and the material resembled a sponge in areas of massive attack. The results of the thruster failure and subsequent analysis indicated that, although stainless steel is an excellent catalyst for decomposing ammonia, it has no long-term corrosion resistance to ammonia.

During the time period that the failure analysis was being performed on the thruster, a long-term materials compatibility assembly was also subjected to an electron beam probe analysis. This assembly consisted of a tubular heater element and stainless steel flow tube coiled and brazed to a nickel core. The heater element had an Inconel 600 sheath, magnesium oxide insulation, and a Nichrome V element wire. The flow tube was type 304 stainless steel, and the braze material was AMI-102, which is an alloy containing 15.2 percent chromium, 9 percent silicon, and the balance nickel. This assembly had been in test in a vacuum environment for a period of 4308 hours, during which it was maintained at 1800°F for 2756 hours. A view of the sectioned assembly, mounted in plastic for analysis, is shown in Figure 38. An enlarged view of a small area of the assembly is shown in Figure 39. The areas that were analyzed are identified in this figure. In addition to the assembly that had been in test, an assembly in an as-brazed condition was also sectioned and its constitutents analyzed with an electron beam probe. The results of the analysis of the exposed and as-brazed assemblies are listed in Table III.

The most important result of the analysis of the heater element samples is evident from the data presented in the table; i. e., the tendency for elemental composition of the components in contact to become uniform. This trend toward uniform composition is due to solid-state diffusion of the component materials. The diffusion between the components changed their structural characteristics, as can be seen in Figure 39. This shows the profusion of voids that developed as the result of the interdiffusion of component material. The result of this analysis indicated that materials in intimate contact on the thruster core would have to be of the same composition.

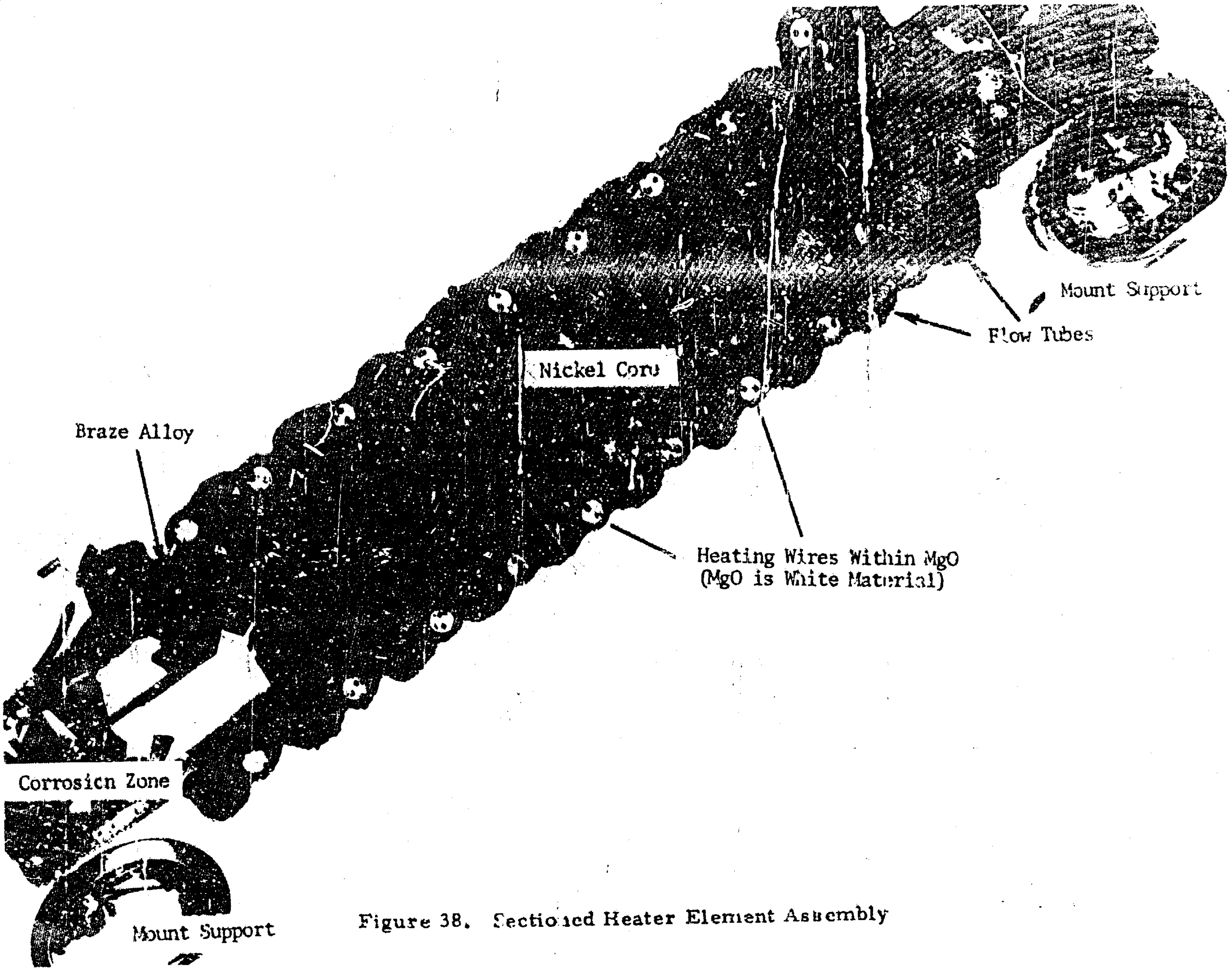

Figure 38. Sectioned Heater Element Assembly

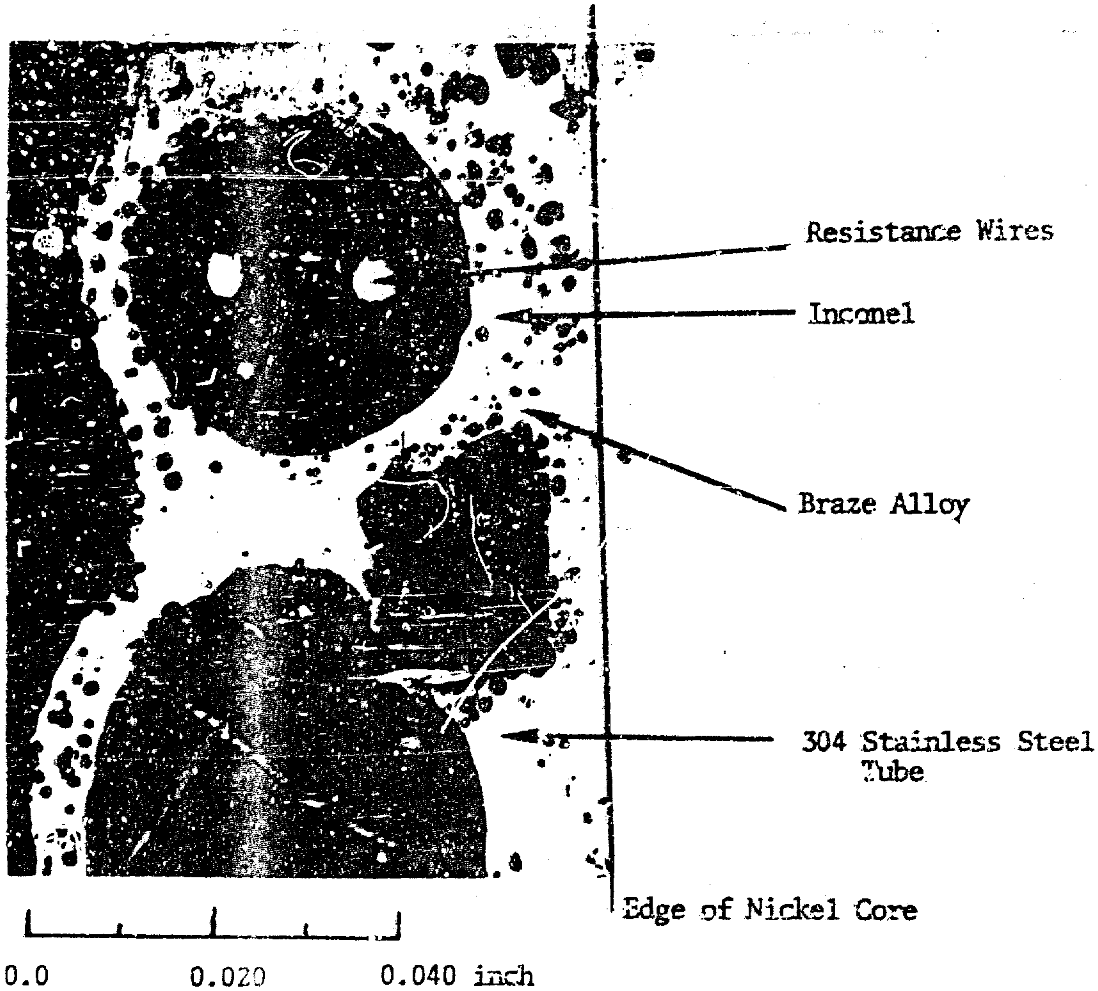

Figure 39. Photomicrograph of Heater Element Assembly

The dark coating on the interior surface of the nozzle expansion core, Figure 33, was analyzed with an electron beam probe. Formation of this coating coincided with the degradation of thruster thermal performance. The analysis indicated that this coating was composed of essentially pure carbon. The presence of a carbon layer on the nozzles would result in a change of a factor of five in their surface thermal emissivity. This change probably caused a large increase in the thruster heat loss due to thermal radiation from the nozzles. The source of the coating was pump oil molecules that cracked as they collided with the hot nozzle surface. A dark coating did not form on the nozzles of subsequent thrusters. This was due to more effective trapping of the diffusion pump used in the test system. The diffusion pump baffles were water cooled during testing of the first thruster, and liquid nitrogen cooled during subsequent testing.

Table III. Assembly Component Chemical Composition

Component	Element, Weight Percent Corrected to the Nearest 1 Percent	
	As Brazed	Exposed
1. Stainless Steel Flow Tube		
Iron	67.0	35.0
Nickel	12.0	51.0
Chromium	21.0	13.0
Silicon	0.2	1.0
	100.2	100.0
2. Inconel 600 Sheath		
Iron	7.0	26.0
Nickel	78.0	59.0
Chromium	15.0	15.0
Silicon	nil	0.2
	100.0	100.2
3. Braze Alloy		
Iron	4.0	28.0
Nickel	75.0	56.0
Chromium	19.0	14.0
Silicon	2.5	2.0
	100.5	100.0

5.2 SECOND ACSKS THRUSTER

The selection of construction materials for the second ACSKS thruster (all metallic components were nickel) was based on the results of the analysis of the first ACSKS thruster, the heater element/compatibility test assembly, and data obtained from tests of the compatibility of various materials with ammonia. This thruster, however, failed after 106 days of operation. The failure resulted from porosity that had developed in the flow tube walls, extending along the major portion of the thruster core. The region of maximum porosity occurred at the hottest section of the core. The thruster core was sectioned for both visual inspection and electron beam microprobe analysis. Photographs of parts of the sectioned thruster are shown in Figures 40 and 41.

There is evidence in all of the photographs of a gap between the flow tubes and their grooves. This probably occurred during the wrapping process when the tubing was coiled in the core grooves. These voids did not appear to affect thruster performance, because the thruster did perform satisfactorily prior to the porosity formation.

The flow tube cross sections shown in Figure 40 are grossly distorted, and are cracked in some instances. The distortion could have resulted from stress relieving of the electroplated layer during high temperature operation. The electroplated nickel coating on the heater element, and also that over the flow tubes, was deposited in several layers. The unit was heated to 500°F after each layer was plated for the purpose of stress relieving the plating. This may not have been effective for the very large total electroplated thickness. There is a second possible cause; i.e., that the distortion of the tubes did not occur until after propellant began penetrating the flow tube wall. In that case, the movement of the plating could have resulted through an interaction between the nickel plating and the ammonia and its decomposition products. The maximum amount of flow tube distortion appears in the region of maximum porosity. This can be seen by comparing the thruster section in Figure 41 with that in Figure 40, which had the higher porosity.

The thruster core section shown in Figure 40 was used for a nitrogen analysis with an electron beam microprobe. No nitrogen was detected in

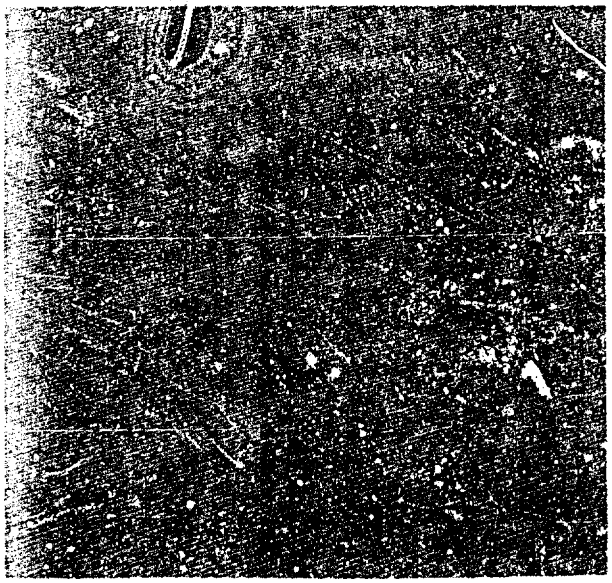

Figure 40. Midcore Thruster Section, ACSKS -2

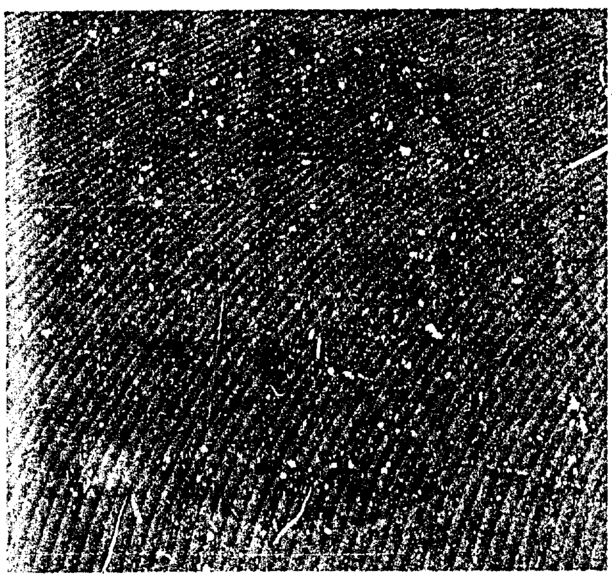

Figure 41. Entrance End Core Section, ACSKS -2

either the flow tube walls or the surrounding electroplated areas, although the flow tube wall material was brittle. At the operating temperature of the thruster core, the nitrides of nickel are unstable. However, during the ammonia decomposition process, unstable nitrides would form with the wall material as intermediate species. It is possible that some of the nitrogen liberated by the decomposition of these intermediate compounds could diffuse into the flow tube wall material rather than into the propellant flow stream. In this case, the nitrogen would be involved in reactions and dissociations, especially at the grain boundaries of the tube wall material. The grain boundaries would present the most active sites for reaction and the easiest path for migration. This process would account for the complete embrittlement of the flow tube with the presence of, at most, a negligible quantity of nitrogen in the material. A similar behavior of metals in contact with corrosive media as well as hydrogen and helium is discussed in Reference 3.

The selection of nickel 200 for the flow tube material of this thruster was based on the results of compatibility tests performed during the failure analysis period of the first thruster. During these tests, nickel 200 tube samples were continuously exposed to ammonia for periods in excess of 80 hours at temperatures of 1000°F and 1650°F. The tube samples appeared to sustain only moderate change in physical properties and appearance during this exposure period. The depth to which structural changes of the nickel had progressed was small, relative to the tube wall thickness. The exposure time of the nickel to ammonia in the compatibility tests was considerably in excess of the integrated time exposure of the propellant flow tubes during a 1-year mission (< 10 hours). However, the flow tubes of the second thruster failed after an integrated time exposure of approximately 0.3 hour. The data obtained from ammonia compatibility tests in which the material samples were subjected to a periodic ammonia exposure also verified that failure would occur in certain materials with short integrated time exposure. Those materials that did fail with short exposure times were also materials that exhibited good catalytic activity for ammonia decomposition. Materials tested that were resistant to ammonia attack exhibited essentially no catalytic activity for ammonia decomposition.

5.3 THRUSTER ANALYSES CONCLUSIONS

The results of these compatibility tests appear to verify the formation of unstable nitrides and migration of nitrogen within materials that are effective decomposition catalysts. Also, this process appears to proceed during periods between exposure to ammonia. One material that exhibited excellent resistance to ammonia attack, but essentially no catalytic activity for its decomposition, was Inconel X750. This behavior appears to be due to the formation of stable chromium nitride on the alloy surface exposed to ammonia. Chromium was found to diffuse from the interior of the material sample which enhanced both the thickness and uniformity of the nitride surface. The stabilizing elements in the alloy, aluminum and titanium, appear to form nitrides in the grain boundaries of the exposed surface. This would inhibit the migration of nitrogen throughout the material. As a result of this data, Inconel X750 was selected as the flow tube material for the third ACSKS thruster. Because it did not have the required catalytic activity for ammonia decomposition, the flow tubes were fabricated with a nickel liner. This liner was expected to present a catalytic surface to the flowing propellant stream. Although nickel is embrittled as a result of exposure to ammonia, it did not exhibit any dimensional change, and retained its special configuration when not subjected to any physical loading. A thin aluminum oxide layer was sandwiched between the nickel liner and the Inconel X750 outer tube. This aluminum oxide layer serves as a barrier for the interdiffusion of the constituents of the tube/liner combination. This type of propellant flow tube proved satisfactory for decomposed ammonia thruster use.

6. CONCLUSIONS AND RECOMMENDATIONS

The results of the life test indicate that an electrically heated ammonia propulsion system can be utilized for spacecraft attitude control and station keeping maneuvers. There were no interface problems encountered when operating the control electronics, thruster, and zero-gravity feed system in closed loop. The final test system exhibited the reliability necessary for long-term spacecraft operation. The total lapsed time of the test, including the demonstration test, was 752 days. During this time period, the system was operated in closed-loop for 540 days.

6.1 CONTROL ELECTRONICS CONCLUSIONS

The control electronics demonstrated excellent control mode characteristics. The one abnormal operating characteristic of the control electronics was a shift in null point during the transition from atmospheric to vacuum environment. This effect can be eliminated by the use of a matched pair of FET's which are currently available. In addition, a lower current in the FET circuit might increase their stability.

6.2 THRUSTER CONCLUSION

The ACSKS thruster demonstrated high thermal and specific impulse performance. The thruster reliability was not demonstrated until the final stage of the test program. The results of the thruster failure analysis and material compatibility test analyses performed during the program were successfully applied to thruster design. The composite flow tubes used on the final thruster exhibited the required reliability necessary for spacecraft application. The results of these analyses also were responsible for the evolution of the plasma spray technique for attachment of the flow tubes to the core. By this technique, the composition of the bonding material can be more nearly matched to that of the structural material. Also, the structural component and thruster heater element are not subjected to the extreme temperature necessary for a satisfactory braze bonding.

High thruster thermal performance was achieved by the use of super insulation. This type of insulation consists of alternate layers of a thin, low-emissivity foil, such as molybdenum, and a woven quartz fabric. One problem that was encountered with the use of super insulation was reproducibility in assembly of the insulation package. In several instances, it was necessary to reinsulate a thruster to obtain the minimum potential heat loss. The problem of obtaining a reproducible insulation characteristic has been solved by using a thinner quartz cloth than that available at the time of thruster fabrication.

The thruster design demonstrated that nearly complete decomposition of ammonia, necessary for high specific impulse performance, could be achieved by using the concept of diffusion-controlled, wall-catalyzed reactions. The use of this concept eliminated the need for a catalyst bed to achieve the high performance. The delivered specific impulse, and therefore the fraction ammonia decomposed in the flow tubes, of the final ACSMS thruster was a function of the operating thrust level. High performance operation with this thruster was achieved at thrust levels above that required by the control system. The high specific impulse can be maintained at lower thrust levels with thrusters having composite flow tubes by decreasing the flow passage area and increasing the tube length. These changes will produce the required turbulence in the propellant flow stream to achieve nearly complete decomposition.

6.3 FEED SYSTEM CONCLUSIONS

The zero-gravity feed system designed for this program performed within specifications throughout the entire life test. The functional feasibility of the capillary tube concept for vapor-phase propellant delivery was demonstrated by the test. The propellant delivery system accepted either liquid or vapor phase ammonia from the storage tank and supplied vapor phase ammonia only to the distribution system plenum. It performed this function at all flow demands imposed by the various control system operating modes. In addition, the pressure regulation capability, reliability, and versatility of the pressure control circuit/capillary tube combination were demonstrated. The feed system supplied the vapor phase propellant within the pressure band necessary for predictable and reproducible thruster performance.

One improvement that could be made in the feed system design is the incorporation of a lead-lag network in the electronic switch circuit. This network would make the switch responsive to both delivery pressure and rate of change of delivery pressure. The rate sensitivity would decrease the difference in pressure control band between vapor entering the capillary tubes and liquid.

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13. ABSTRACT

This report describes a life test of an attitude control and station keeping subsystem which uses an electrically-heated ammonia propulsion system. A high-performance ammonia thruster and a zero-gravity ammonia feed system were operated in response to the stimulus of control electronics typical of future military spacecraft. This test was a continuation of a successful one-month demonstration test performed as the final task of a system development program. In total, the test was continued for a period of 752 days, during 540 days of which the system was operated closed-loop. The feed system was operational for the entire test period. It successfully regulated delivery pressure to within ± 3 percent deadband under a wide variety of environmental and duty cycle conditions. Three different four-nozzle thrusters were tested, two of which failed due to ammonia corrosion after periods of 5 and 3-1/2 months. The test of the third thruster was terminated after a 6-month period of successful operation. No ammonia corrosion was evident. The thruster characteristics included a delivered specific impulse of 240 seconds at 1500°F. A power level of 14 watts was required to maintain this temperature with no flow.

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KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Attitude Control						
Ammonia Propulsion						
Control Electronics						
Resistively Heated Thruster						
Zero-Gravity Feed System						
Materials Compatibility						